AN ENVIRONMENTAL AND POLICY EVALUATION OF CELLULOSIC ETHANOL

A Dissertation

by

LISA DIANE HURTADO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2011

Major Subject: Interdisciplinary Engineering

AN ENVIRONMENTAL AND POLICY EVALUATION OF CELLULOSIC ETHANOL

A Dissertation

by

LISA DIANE HURTADO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by:

Co-Chairs of Committee,	Robin Autenrieth
	B. Don Russell
Committee Members,	Marvin Adams
	Arnold Vedlitz
Chair of Interdisciplinary Engineering Program,	Robin Autenrieth

May 2011

Major Subject: Interdisciplinary Engineering

ABSTRACT

An Environmental and Policy Evaluation of Cellulosic Ethanol. (May 2011)

Lisa Diane Hurtado, B.S., Texas A&M University; M.S., Texas A&M University

Co-Chairs of Advisory Committee: Dr. Robin Autenrieth
Dr. B. Don Russell

As the global demand for energy rises, there are significant efforts to find alternative energy sources. In the United States (US), these efforts are primarily motivated by a desire to increase energy security and reduce the potential impacts on climate change caused by carbon dioxide emissions from the burning of fossil fuels. Biofuels are considered a potential partial solution, which are being encouraged through public policy. Cellulosic ethanol is a biofuel that is required in increasing amounts over time as part of the Renewable Fuel Standards. Thus, researchers are exploring the environmental impacts of using this biofuel on a large scale. This dissertation research performed an environmental evaluation using the Life Cycle Assessment technique on Bioenergy Sorghum, a crop which was specifically produced as an energy crop, used in a conversion process (MixAlco version 1) that can produce cellulosic ethanol.

Results indicate that the conversion process is highly optimized with minimal environmental concerns. Analysis of the crop production, however, demonstrate that further investigation is warranted regarding the depletion of natural resources and emissions from the fertilizers and pesticides/herbicides, due to large scale production of energy crops. A new policy is proposed to support the sustainable, environmentally responsible development of cellulosic ethanol in the US.

DEDICATION

To JE, Cisco, and Catarina

ACKNOWLEDGEMENTS

Thank you to Johnny, Cisco, and Catarina Hurtado for love and sacrifice; Don and Shirley McCrea, and John and Linda Hurtado for faith; Jorja Kimball and Nancy Watson for peace in troubled times; Karan Watson for mentorship; Robin Autenrieth, B. Don Russell, Marvin Adams, and Arnold Vedlitz for guidance and forbearance; Mark Holtzapple, Cesar Granda, and Bill Rooney for generosity; David Allen for seeing the possibility of it; and David Boyle for telling me to do it.

TABLE OF CONTENTS

Page

ABSTRACT iii

DEDICATION iv

ACKNOWLEDGEMENTS v

TABLE OF CONTENTS...vi

LIST OF FIGURES viii

LIST OF TABLES ix

1. INTRODUCTION 1

2. LITERATURE REVIEW 4

3. ENVIRONMENTAL EVALUATION 11

 3.1 Goal and Scope Definition 12
 3.2 Life Cycle Inventory Analysis 14
 3.3 Life Cycle Impact Assessment 23
 3.4 Life Cycle Interpretation 39

4. POLICY EVALUATION.. 62

 4.1 Current Policy Overview 62
 4.2 Impacts of Scaling Up 69
 4.3 Stakeholders and Decision Makers... 82
 4.4 Policy Recommendations- Cellulosic Ethanol Enhancement Act 90

5. CONCLUSIONS AND RECOMMENDATIONS 99

 5.1 Motivating Factors 99
 5.2 Dissertation Research Conclusions and Recommendations........................ 100
 5.3 Future Research Recommendations 101

Page

REFERENCES 104

APPENDIX A 117

VITA 126

LIST OF FIGURES

Page

Figure 1. Yield of Various Biomass Feedstock 6

Figure 2. Life Cycle Assessment Framework (modified from ISO 14040) 12

Figure 3. Overview of the MixAlco Conversion Process, Version 1 15

Figure 4. Pretreatment and Fermentation of Piles 19

Figure 5. Pretreatment/Fermentation Life Stage Process Flow 20

Figure 6. Primary Operation Life Stage Process Flow 22

Figure 7. Life Cycle Impact Assessment Procedure (Guinee 2001) 24

LIST OF TABLES

Page

Table 1. US Available Biomass Resources (Perlack et al. 2005) 5

Table 2. Energy Density of Some Biomass, Biofuels, and Fossil Fuels 7

Table 3. Data Pedigree Matrix (modified from (Guinee 2001)) 15

Table 4. Acidification Potential Impact Assessment Results 27

Table 5. Climate Change Potential Impact Assessment Results 28

Table 6. Freshwater Aquatic Ecological Toxicity Potential Impact Assessment Results 29

Table 7. Terrestrial Ecological Toxicity Potential Impact Assessment Results 30

Table 8. Eutrophication Potential Impact Assessment Results 31

Table 9. Human Toxicity Potential Impact Assessment Results 32

Table 10. Abiotic Depletion Potential Impact Assessment Results 35

Table 11. Land Competition Potential Impact Assessment Results 37

Table 12. Environmental Profile (for one conversion plant producing 170 M liters/yr) . 38

Table 13. Percent in Each Category Normalized by Reference Category Indicators for the World and the European Union 40

Table 14. Comparison of Impact of Different Fuels and Crops for Several Impact Categories 44

Table 15. Comparison of Impact of Different Crops and the Same Crops with Different Nitrogen Fertilizers for a Few Impact Categories and Emissions .. 49

Table 16. Percent Change in Impact Potential Caused by a 1% Increase in Emission Rate 57

Table 17. Federal Renewable Fuel Standards (as given in EISA, Section 202 - not showing recent changes) 65

Table 18. State-Level Policies that Affect Alternative Fuel Production (modified from National Association of State Energy Officials 2011) 68

Page

Table 19. Percent Impact in Each Category Normalized by Reference Category Indicators for the World When Scaled to RFS Amounts for 2022 71

Table 20. Inventory Analysis Inputs for Resource Provisioning Life Stage 117

Table 21. Inventory Analysis Outputs for Resource Provisioning Life Stage 118

Table 22. Inventory Analysis Inputs for Pretreatment/Fermentation Life Stage 119

Table 23. Inventory Analysis Outputs for Pretreatment/Fermentation Life Stage....... 119

Table 24. Inventory Analysis Inputs for Primary Operation Life Stage 120

Table 25. Inventory Analysis Outputs for Primary Operation 120

Table 26. Sensitivity Analysis for Nitrous Oxide Emissions 121

Table 27. Sensitivity Analysis for Ammonia Emissions 122

Table 28. Sensitivity Analysis of Nitrogen Emissions 123

Table 29. Sensitivity Analysis of Phosphorus Emissions 124

Table 30. Sensitivity Analysis of Atrazine Emissions 125

1. INTRODUCTION

The International Energy Agency (IEA) (International Energy Agency 2009) is projecting a rise in world primary energy demand of 1.5% per year until 2030; with three quarters of this increase coming from China, India, and the Middle East. "Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand and Vietnam collectively make up one of the world's most dynamic and diverse regions, with an economy as large as Canada and Mexico combined, and a population that exceeds that of the European Union (International Energy Agency 2009)." The consumption rate of this group of countries is already comparable to the Middle East and is projected to grow rapidly. United States (US) energy consumption is also projected to increase from 2009 to 2035, and fossil fuels are projected to provide 78% of the energy needed in the US in 2035 (Energy Information Administration 2011). Global oil demand is projected to grow by 1% per year on average (International Energy Agency 2009). The transportation sector accounts for 97% of this projected increase.

The IEA further indicates that the majority of this oil will need to come from Organization of the Petroleum Exporting Countries (OPEC) countries where most of the conventional oil resources are located. US domestic crude oil production is projected to increase only very slightly; from 5.4 million barrels per day in 2009 to 5.7 million barrels per day in 2035 (Energy Information Administration 2011). These projections indicate that much of the fossil fuel needed for US energy demands will continue to be imported. Many of the countries from which the oil is imported are politically unstable or even

____

This dissertation follows the style of *Journal of Environmental Engineering*.

the hostile to the western world. Reliance on foreign sources for energy puts the US in a vulnerable position (Institute for the Analysis of Global Security 2004). Energy independence (reducing the amount of imported fuel) is seen as a path to increasing energy security. US Secretary of Energy, Steven Chu announced in August 2009 that the American Recovery and Reinvestment Act (ARRA) projects “will provide vital funding and new tools for research aimed at strengthening America’s energy security…(U.S. Department of Energy 2009).”

In addition to energy security concerns, the continued and increased use of fossil fuels is also seen as an environmental issue. Because the energy in fossil fuels is derived from fossilized carbon, when the carbon is combusted it is released into the atmosphere as carbon dioxide. The carbon dioxide accumulates in the atmosphere, where it will persist for several centuries (Griffin 2003). Carbon dioxide is one of the gases known as "greenhouse gases”. The concentration of these gases in the atmosphere inhibit thermal radiation from escaping to space and thereby contributing to the warming of the earth, a phenomena known as global warming. There is now general agreement among the scientific community, if not the population in general, about the reality of anthropogenic climate change (International Energy Agency 2009; Oreskes 2004).

Several alternatives are being explored to address energy independence and climate change concerns (Samaras and Meisterling 2008). Biofuels and blends of biofuels (Mohamadabadi et al. 2009) are currently being used to diversify the US energy portfolio. Approximately 45 billion liters of biofuels were produced in 2009, mostly consisting of corn ethanol with a small percentage of biodiesel. Public policy is currently in place to encourage the growth of the biofuels industry, and especially cellulosic ethanol. No large commercial scale cellulosic ethanol plants are currently operating in the US. Improving fuel economy through hybrid electric vehicles (HEVs), and plug in hybrid vehicles (PHEVs) is also a possibility. Some HEVs, such as the hybrid Ford Escape (Cogan 2009), provide a flex fuel option which holds promise for increasing fuel efficiency even more and leveraging the benefits gained by using biofuels.

This dissertation begins with a review of current literature on the environmental and policy investigations of alternative transportation energy, including biofuels. Next an environmental evaluation is performed that focuses on cellulosic ethanol in particular as a potential partial solution to reducing US dependence on fossil fuels. Environmental inputs and outputs are discussed and a detailed Life Cycle Assessment for one process is presented to inform the environmental evaluation of cellulosic ethanol. Next some relevant externalities for cellulosic ethanol are discussed and a policy evaluation is presented.

2. LITERATURE REVIEW

Biofuels offer the potential to increase energy security and decrease greenhouse gas emissions. This literature review will discuss works that have investigated various aspects of the potential use of biofuels in general, and cellulosic ethanol in particular.

One of the first considerations for the use of biofuels is availability of biomass. In April 2005 the DOE produced a report which was designed "…to determine whether the land resources of the United States are capable of producing a sustainable supply of biomass sufficient to displace 30% or more of the country's present petroleum consumption…(Perlack et al. 2005)." This investigation concluded that the US is capable of meeting this level of food, feed, and fuel demands. The amount of biomass sustainably removable from agricultural lands was estimated to be almost 1 billion dry tonnes annually (in 35 to 40 years). The many types of biomass considered available are shown in Table 1.

Flesher (2009) questioned the results of this study and whether or not there is actually enough biomass for our needs. Flesher presents environmental concerns about the use of waste wood as biomass for alternative fuels because it can cause soil erosion and other harm to the forests. In addition, Perlack et al. (2005) did not address the significant potential social/ethical effects of using resources in this way and the effect using these resources for fuel will have on the cost of food and feed. Pimentel et al. (2009) discussed the ethical and environmental dilemma of using food crops for fuel, and also that of using land and water resources that could be used for food for humans and/or feed for animals, when 60% of the humans in the world are malnourished. Pimentel et al. (2009) also claim that corn ethanol increases the price of "US beef, chicken, pork, eggs, breads, cereals, and milk more than 10% to 30%."

Table 1. US Available Biomass Resources (Perlack et al. 2005)

Forest Resources	**Agricultural Resources**
Primary	**Primary**
Logging residues	Crop residues from major crops
Excess biomass from timberlands	Grains used for ethanol, biodiesel, and bioproducts
Fuelwood extracted from forestlands	Perennial grasses
	Perennial woody crops
Secondary	**Secondary**
Wood processing mill residues	Animal manures
Pulping liquors	Food/feed processing residues
Tertiary	**Tertiary**
Urban wood residues	Municipal Solid Wastes

Others share this ethical concern, and are looking for ways to minimize the impact. Gopalakrishnan et al. (2009) investigated the viability of using marginal land resources and nitrate-contaminated water resources to produce biomass. Results indicated that utilizing land resources such as roadway buffer strips, and brownfield sites could make a significant contribution to the land resources needed to produce biofuels. Additionally, results indicated that water resources that were degraded, such as nitrate-contaminated groundwater and wastewater could be used to increase the productivity of feedstocks.

Using highly productive biomass also reduces the depletion of natural resources. Some examples of the productivity or yield of certain feedstocks are given in Figure 1. The corn yield assumes the US average (143 bushels per acre-year) with 15% moisture. Yields of 20 dry tonnes per acre year for sweet sorghum, and 30 dry tonnes acre-year for other sorghum varieties have been demonstrated in Texas test plots (Lau et al. 2006). Energy cane yields of 30 dry tonnes per acre-year have been demonstrated in Puerto Rico test plots (Alexander 1985). Water hyacinth can produce between 60 and 80 dry tonnes per acre-year (Prabu 2006). This data indicates that there are other significantly more productive feedstocks than corn that could be used for ethanol. However, these cellulosic feedstocks require different processing and the process for making cellulosic ethanol has not yet been accomplished on a commercial scale. Nevertheless, these differences in yield provide strong incentive to move cellulosic technology forward.

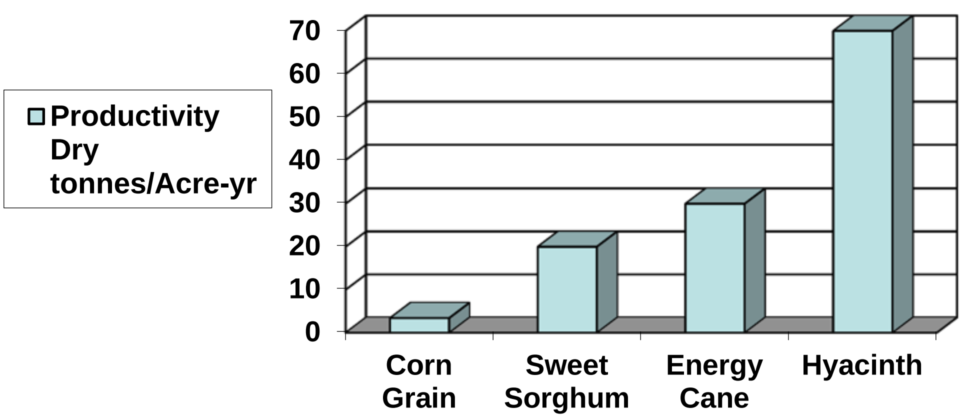

Figure 1. Yield of Various Biomass Feedstock

The impact of resource depletion also can be decreased by using biomass with a high energy density. While biomass in general has less energy per pound than fossil fuels, some types of biomass have higher energy densities than others. The energy densities of some types of biomass, biofuels and fossil fuels are compared in Table 2 (Amphlett et al. 1998; Elert 2009; Thomas 2000). From this comparison, it can be seen that fossil fuel sources provide at least twice the energy density of biomass sources, and some crops can rival corn ethanol in energy density (Table 2). Many of these crops are cellulosic, providing another motivation for the production of cellulosic ethanol.

Table 2. Energy Density of Some Biomass, Biofuels, and Fossil Fuels

Biomass or Fuel	**Energy Density (MJ/Kg)**
Gasoline, Automotive	44.4-45.8
Diesel	42.5-45.3
Oil, crude	41.9
Corn Ethanol	23.4-26.8
Wood, oven dry	20
Cotton hulls	19.4
Soybean stalks	19.4
Sugar cane bagasse	19
Maize, cobs	18.9
Sorghum bagasse	18.9

When considering resource depletion, it is also important to ensure that the energy used to make the fuel is significantly less than the energy the fuel provides. This issue has been examined extensively by several researchers. Pimentel et al. (1994) analyzed the total fossil energy expended to produce ethanol from corn, and found a net energy loss. Cleveland (2001) investigated the energy returned on the energy invested for fossil and biofuels by aggregating energy flows (using exergy). Results indicate that while the net gain for fossil fuels is declining (it is becoming more difficult to extract and must be imported from far away), it is still significantly higher than for corn ethanol. Shapouri et al. (2003) looked at several studies conducted calculating the net energy value of corn ethanol. Results indicate that the variations in data and assumptions for the studies cause a wide range of net energy estimates. Shapouri et al. (2003) further conclude that technological advances in the conversion process and agricultural practices have led to a rise in the net energy gain of corn ethanol, which they calculated as a small net gain. Patzek, et al. (2005) studied the overall energy balance of the corn ethanol conversion process and conclude that 65% of the energy is lost in the conversion process. Greene and Roth (2006) reviewed publications on energy balances of both corn and cellulosic ethanol. This investigation revealed that both corn and cellulosic ethanol productions provide an energy gain on the fossil energy invested. However, the results indicate that the gain is significantly more for cellulosic ethanol. In summary, corn ethanol provides only a small energy advantage. The desire to improve this energy advantage provides another incentive for the production of cellulosic ethanol.

Another aspect that has been investigated regarding the use of biofuels includes several potential environmental impacts. Some comprehensive environmental analyses were performed on various biofuels. Kaltschmitt et al. (1997) presented a study on a number of bioenergy carriers compared to fossil energy carriers. MacLean et al. (2000) performed a high level comparison of alternative fuels to fossil fuels. Both Puppan (2002) and Hill et al. (2006) performed an environmental impact assessment on biodiesel and bioethanol. Granda et al. (2007) compared the environmental impact of bioethanol and biodiesel fuels. Von Blottnitz and Curran (2007) reviewed published life cycle studies on biofuels, which had been performed over several years to various degrees of completeness and using a variety of methods. Results from these studies indicate that biofuels have lower greenhouse gas emission than their fossil counterparts. However, some environmental factors, such as toxicity to humans and the ecology, were found to be worse for biofuels than for fossil fuels. Some of the researchers reviewed here used versions of Life Cycle Assessments, which helped inform the analyses performed in this dissertation (Section 3).

Various degrees of policy analyses regarding the potential use of biofuels have also been performed. MacLean et al. (2000) presented a cost/benefit analysis for alternative automobile fuels, showing that in order for biofuels to be cost attractive, emission and fuel economy regulations would likely need to be tightened. Puppan (2002) gave a short review of the bioenergy policy current at the time, indicating that policy existed or could be crafted that might be able to make biofuels an economically advantageous alternative fuel. Hill et al. (2006) discussed the economic effect of federal crop subsidies that lower the price of corn and soybeans, making the biofuels created from these crops more cost-competitive with fossil fuels. Romm (2006) reviewed literature on alternative fuels and vehicles in light of current policies and environmental concerns and drew conclusions about where the US public policy agenda is moving; his conclusion was that hybrid cars with flex fuel are the most promising alternative fuel vehicles for the near future. Wyman (2007) looked at what policies are necessary to advance cellulosic ethanol and concludes that research that advances the technology to overcome the difficulty associated with chemically breaking down cellulosic biomass should be aggressively funded. Granda et al. (2007) discussed driving forces for using biofuels as both economics and energy security, where economics drives industry and energy security drives government. Charles, et al. (2007) analyzed the benefit of biofuels from an environmental, social, and economic perspective and evaluated current policy instruments used to promote biofuels. Results from this analysis indicate the need for a balanced long-term policy approach to affect a fundamental reorientation of agriculture to achieve greater production of cellulosic ethanol, also known as second generation biofuels. Samaras and Meisterling (2008) discussed policy implications of using PHEVs, driven by the associated coupling of transportation and electric power generation, along with the aging electrical power infrastructure. Muller (2009) discussed the land and water competition between food and fuel, and investigated alternatives and policies designed to increase sustainability in agriculture for biomass production. Balat and Balat (2009) looked at recent trends in bio-ethanol as a fuel and conclude that bio-ethanol, the most widely used biofuel in the world, “will continue to be developed as a transport fuel produced in tropical latitudes and traded internationally, for use primarily as a gasoline additive.”

The research discussed in this section was used to inform an environmental and policy evaluation of cellulosic ethanol as a potential partial part of the US energy portfolio.

3. ENVIRONMENTAL EVALUATION

Cellulosic ethanol has the potential to reduce greenhouse gas emission compared to fossil fuels. However, as the literature review indicated, all of the inputs and outputs to the process must be considered before the process is evaluated as better for the environment than fossil fuels. The research in this section identifies relevant environmental concerns through the use of a Life Cycle Assessment (LCA) example.

This section presents a LCA methodology as described in ISO 14040 and 14044 (International Standards Organization 2006a; International Standards Organization 2006b) and further put into operation by Guinee (2001). This standard was used to analyze a cellulosic ethanol conversion process. It is important to note that a LCA does not attempt to quantify any of the *actual* impacts associated with a process being evaluated. The purpose is to establish a link between the process system and the *potential* impact of a particular environmental intervention. Thus, the LCA is not designed to be used for regulatory decisions or risk analysis. However, many of the models used within the LCA are simplified versions of more sophisticated risk analysis and environmental impact assessment models. These models are considered "suitable for relative comparisons of the potential to cause human or environmental damage, but are not indicators of absolute risk or actual damage to human health or the environment (Guinee 2001)."

For this dissertation, the LCA was conducted according to current LCA best practices as given by the Society of Environmental Toxicology and Chemistry (SETAC) (Guinee 1992; Weitz et al. 1998). The LCA proceeds through four phases with some necessary iteration between stages (Figure 2). The four phases of the LCA are: 1) Goal and Scope Definition, 2) Inventory Analysis, 3) Impact Assessment, and 4)

Interpretation. Using the results of the LCA, policy implications are discussed in Section 4.

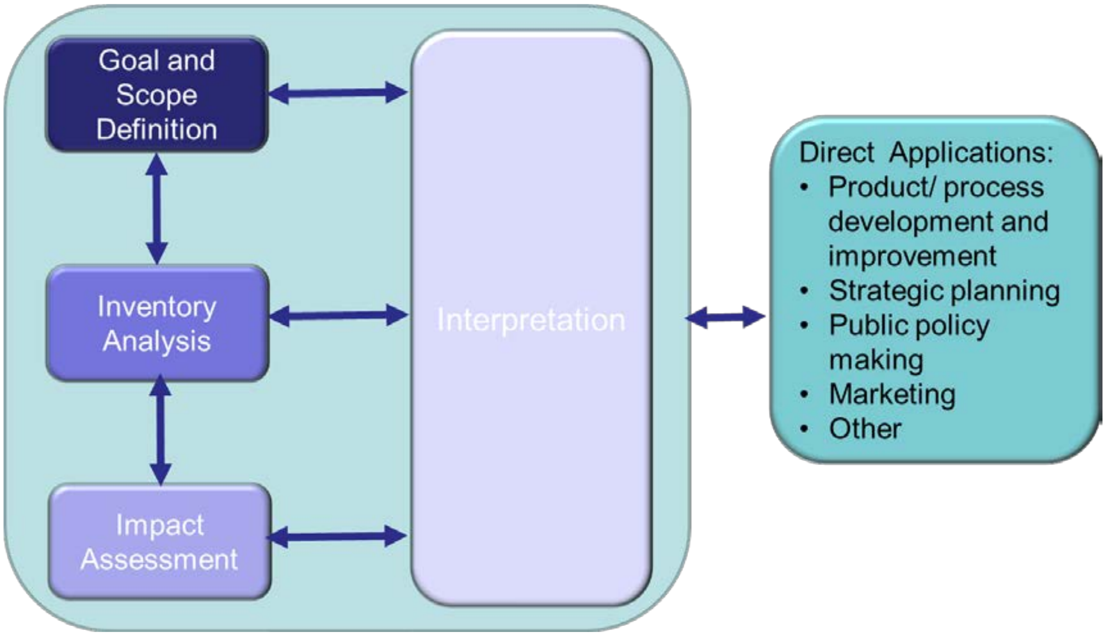

Figure 2. Life Cycle Assessment Framework (modified from ISO 14040)

3.1 Goal and Scope Definition

The goal of this LCA was to evaluate the potential environmental impacts of a biofuel produced by the MixAlco process, version 1, under development at Texas A&M University, which converts cellulosic biomass to produce ethanol or higher alcohols (Elander et al. 2009; Holtzapple and Granda 2009; Sierra et al. 2008; Zhu et al. 2008). This version of the process is at a pilot stage and has not been fully commercialized.

The scope of the LCA began with the growing of the crop and ended with the production of biofuels. A bioenergy crop also under development at Texas A&M

University, Bioenergy Sorghum, was used as the feedstock for this illustration. Recycling or disposal of waste was also discussed. Three life stages were included in the scope of this process: 1) Resource Provisioning, 2) Pretreatment/Fermentation, and 3) Primary Operation. A LCA with these boundaries is often referred to as a "Well-to-Plant" LCA. A more comprehensive analysis, known as a "Well-to-Wheel" LCA, includes the burning of the fuel in various vehicles (engines). A "Well-to-Wheel" LCA is outside the scope of this research because the data required is unavailable given the pilot stages of the process and crop. Although some assumptions could be made and an analysis performed, there would be a large disparity in the quality of the data. This disparity is considered undesirable in LCAs (International Standards Organization 2006a; International Standards Organization 2006b). The scope of this LCA should be considered for any comparisons to other LCAs and when using conclusions drawn from this LCA.

The reference flow for this analysis was a base case conversion plant with a capacity of 320,000 dry tonnes of biomass per year, producing 171 million liters per year fuel (Granda and Holtzapple 2007). Current operating ethanol plants produce between 117 and 594 million liters per year, with the average size being 216 million liters per year (Nebraska State Government 2009). Three functional units were used for this analysis to facilitate comparison with existing published LCA data: energy (mega joules), land area (hectares), and feedstock mass (tonnes). Input and output data were collected associated with each stage of the process for the reference flow given above and related to these functional units as appropriate.

3.2 Life Cycle Inventory Analysis

The Life Cycle Inventory Analysis was performed to obtain the necessary data as detailed in ISO 14044 (International Standards Organization 2006b). Data was gathered for the life stages considered (Resource Provisioning, Pretreatment/Fermentation, Primary Operation) including inputs, outputs, and process flow information, which were used in the Inventory Analysis. For each life stage, data was collected, calculated, and/or estimated from existing literature and personal communication with bioenergy crop and process researchers. The data are given in Appendix A and include an evaluation of the quality (pedigree) of the data with respect to its reliability, completeness, and temporal, geographical, and other technical considerations. This evaluation is accomplished using the Data Pedigree Matrix (Table 3).

3.2.1 Process Overview

As noted previously, this analysis is performed on version 1 of the MixAlco process. Texas A&M process researchers are currently working with Terrabon on a demonstration plant that uses a later version of the MixAlco process (Terrabon 2010). There is a plan to build a commercial scale biorefinery in 2012.

A top-level overview of the MixAlco process, version 1 includes the inputs and outputs that are directly involved in the conversion process (Granda and Holtzapple 2007) (Figure 3). A detailed discussion of each life stage of the process is presented in the following subsections, which includes all inputs and outputs. The LCA begins with the Bioenergy Sorghum being grown and harvested and the resulting biomass being transported to the processing plant. The biomass is placed in a pile and blended with lime. During pretreatment, for increasing bio-digestibility of the biomass, air is blown up through the pile while water is trickled down through the pile.

Table 3. Data Pedigree Matrix (modified from (Guinee 2001))

Pedigree	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Further Technical Correlation
1	Verified data based on measured data	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Less than 3 years of difference from the year of study	Data from area under study	Data from enterprises, processes and material under study
2	Verified data based partly on assumptions, or non-verified data based on measurements	Representative data from a smaller number of sites but for adequate periods	Less than 6 years of difference from the year of study	Average data from larger area that includes area under study	Data on processes and material under study but from different enterprises
3	Non-verified data partly based on assumptions	Representative data from an adequate number of sites but for shorter periods	Less than 10 years of difference from the year of study	Data from area with similar production conditions	Data on processes and materials under study but with different technology
4	Qualified estimate (e.g. by industrial expert)	Representative data but from a smaller number of sites, for shorter periods, or incomplete data for an adequate number of sites and periods	Less than 15 years of difference from the year of study	Data from area with slightly similar production conditions	Data on related processes or materials but with the same technology
5	Non-qualified estimate	Representativeness unknown, or incomplete data from a smaller number of sites and/.or for shorter periods	Age of data unknown, or 15 or more years of difference from the year of study	Data from unknown area or area with very different production conditions	Data on related processes material but with different technology

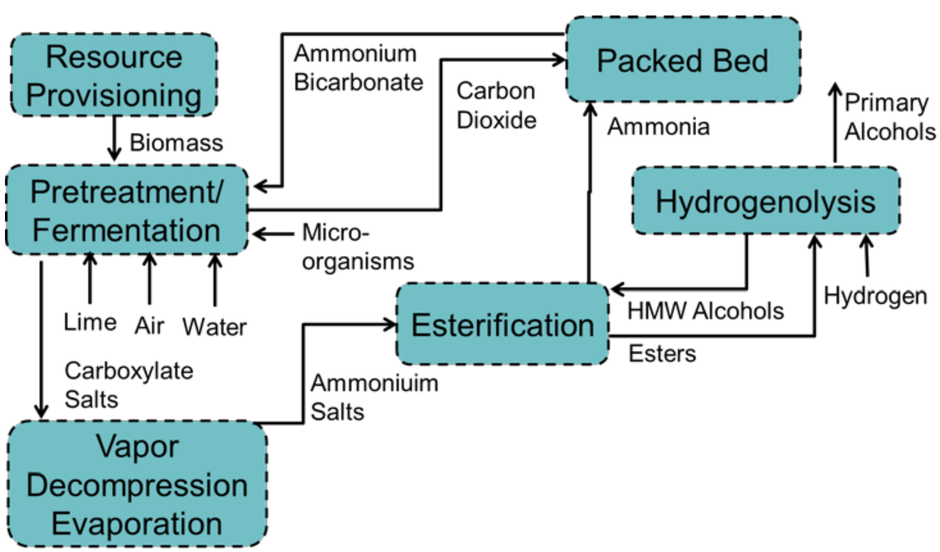

Figure 3. Overview of the MixAlco Conversion Process, Version 1

The lime, combined with the air, helps remove the lignin which makes the biomass more digestible to microorganisms. The pH in the pile drops as the lime is consumed and then the pile is inoculated with anaerobic microorganisms to begin fermentation. These microorganisms digest the biomass to form carboxylic acids, which react with the ammonium bicarbonate to form carboxylate salts.

Water is circulated through the pile to remove the carboxylate salts. The salts are then concentrated using a vapor compression evaporator to make concentrated ammonium salts. These salts are then converted to esters by reacting them with high molecular weight alcohols (shown as HMW Alcohols in Figure 3). The ammonia that results from this step is sent to a packed bed, where it is combined with some of the carbon dioxide released in fermentation to make the ammonium bicarbonate needed previously in pretreatment.

Hydrogen is added and the esters are converted into their corresponding primary alcohols through hydrogenolysis, which also creates the high molecular weight alcohols which are recycled back to esterification step. This process is highly optimized as seen in this overview. Additionally, the power is optimized by using waste heat and burning the left over solid mass for energy to run the process.

3.2.2 Resource Provisioning

The process feedstock used was Bioenergy Sorghum, a version of sweet sorghum that was genetically modified to produce no grain. This feedstock was selected because it was specifically developed for use as a biofuel feedstock (Lau et al. 2006; Miller and Creelman 1980). It is still under development at Texas A&M University and is not currently in commercial production. Sorghum, from which the Bioenergy Sorghum is developed, is a high yield cereal grass that is relatively inexpensive to grow, and has been adapted to climates such that it is able to grow in 35 states in the US (Hons et al. 1986; Lau et al. 2006). Sorghum is also considered a viable feedstock for ethanol production (Barbanti et al. 2006; Caserta et al. 1995; Wang et al. 2008).

Some assumptions were necessary regarding growing and harvesting of the bioenergy crop to facilitate appropriate data gathering. The assumptions made are consistent with standard procedures. The Bioenergy Sorghum was assumed to be grown on land already set aside for agricultural purposes, harvested using green chopping, and then stored in silos. It was also assumed that the feedstock is delivered to a processing plant within a 50 mile radius of the field, and containing manure in a typical amount of 80% feedstock and 20% manure.

The inputs and outputs for the Resource Provisioning life stage are detailed in Appendix A. The inputs from the environment for this life stage included seeds, water, land, fertilizers, pesticides/herbicides, and energy. The quantity of seeds used was obtained directly from crop researchers, and the seed is not in restricted supply. Because Bioenergy Sorghum is a crop specifically grown for the production of biofuels, it was assumed that there was no irrigation (as suggested by bioenergy crop researchers). Land area used for crop cultivation was obtained from Granda et al. (2007) for this crop. The fertilizer used included nitrogen and phosphorous. The amount applied was obtained from the crop researchers. The pesticide/herbicide applied was assumed to be atrazine per recommendation from the Bioenergy Sorghum researchers. The application rate was obtained from a database that is updated and maintained by the Pesticide Action Network North America (Pesticide Action Network North America 2010). LCAs for biomass and biofuels often do not evaluate pesticides/herbicides impacts or only include one or two because data on these chemicals is difficult to find (this will be discussed further in the Life Cycle Interpretation).

The outputs for the Resource Provisioning life stage included emissions to the air, leaching to fresh water, and volatilization to the agricultural soil from the fertilizer and the pesticide/herbicide. The quantities for the emissions from fertilizers were obtained from literature for this or other crops ((Bouwman 1996; Bouwman et al. 2002a; Bouwman et al. 2002b; Crutzen et al. 2008; Intergovernmental Panel on Climate Change 2007c; Petronella et al. 2009; Sharpley A. N. et al. 2003; Zhao et al. 2009), and were based on a percentage of the application rate. The carbon dioxide emissions resulting from the activities of planting, harvesting, and transporting biomass were estimated from a range given in St Clair et al. (2008) for Miscanthus, oilseed rape, and winter wheat. Pesticide/herbicide leaching and volatilization rates were obtained from Kellogg et al. (2000).

3.2.3 Pretreatment/Fermentation

Pretreatment and fermentation begins with the biomass being assembled into several large piles with approximately the same volumes, and proceeds through the piles (Figure 4). After pretreatment has ended and the pile has been inoculated with microorganisms, the fermentation begins. At this point, fresh water is added to the right most pile where it extracts the volatile fatty acid salts produced by the microorganisms. A portion of the circulating stream is added back into this pile and a portion is sent to the next pile, in sequence. Eventually the highly concentrated liquid is removed from the left most pile and sent on to the remainder of the process.

For the Pretreatment/Fermentation life stage it was assumed that the amount of land needed for the Pretreatment/Fermentation was negligible when compared to the amount of land needed for the crop production. The amount of water needed for this life stage was obtained from the process researchers, as well as the amount that was eventually sent to waste water treatment (Granda and Holtzapple 2007).

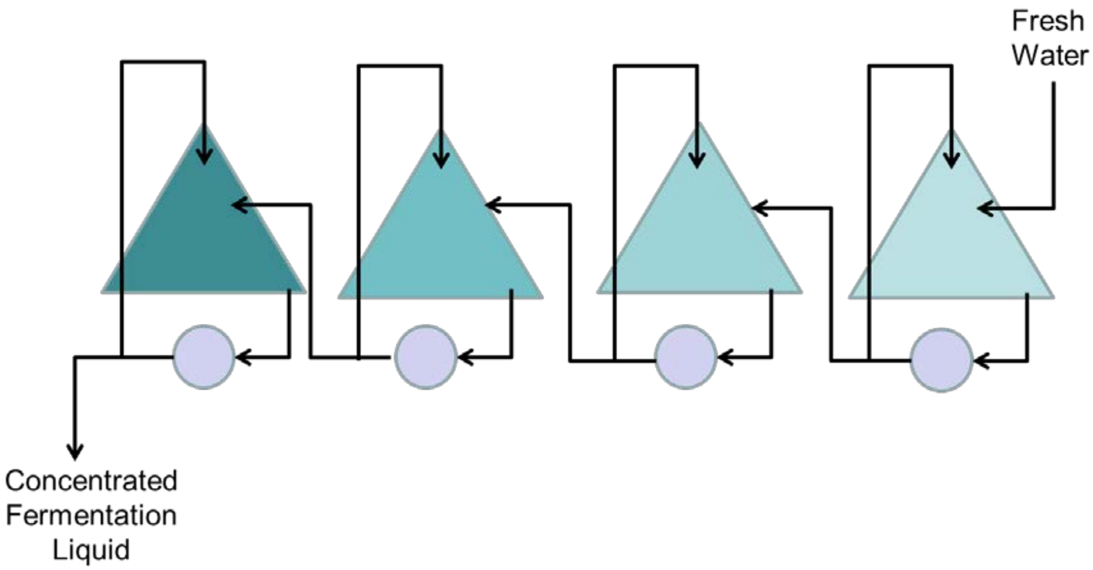

Figure 4. Pretreatment and Fermentation of Piles

The pretreatment is performed to remove the lignin and prepare the feedstock for conversion. Pretreatment begins with adding lime to the biomass feedstock pile, while simultaneously blowing air up through the pile, and pumping water onto the top of the pile (Figure 5). The quantity of lime added from the environment was obtained from the process researchers (Granda and Holtzapple 2007) and is not in restricted supply.

Once the lime is consumed, the pH drops and the fermentation begins. The air is no longer circulated through the pile and a mixed culture of anaerobic microorganisms is added, which generate carboxylic acids, known as volatile fatty acids (VFAs). It was

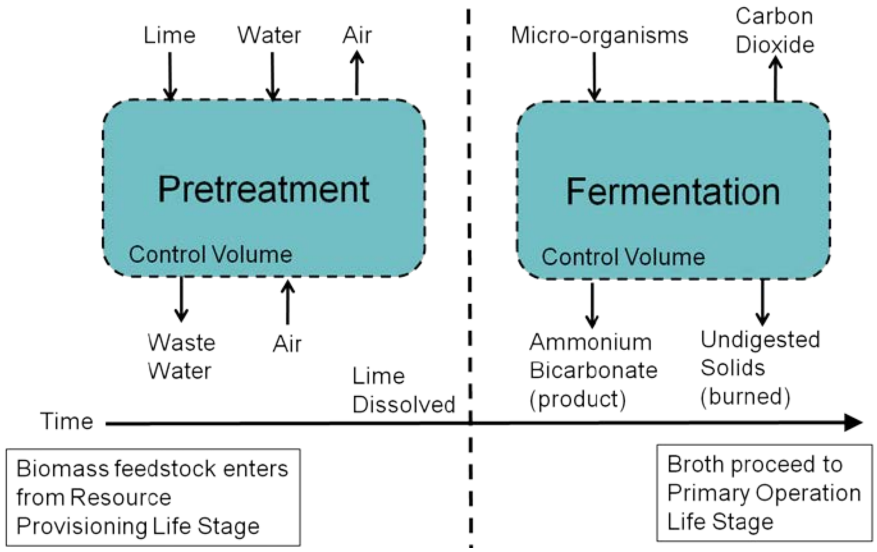

Figure 5. Pretreatment/Fermentation Life Stage Process Flow

assumed that the microorganisms used in this process were taken from a saline environment to ensure their ability to tolerate the high salt environment of the process, and that these micro-organisms were not in restricted supply (as suggested by process researchers). Ammonium bicarbonate is also added at this point, with which the VFAs react to form carboxylate salts. The ammonium bicarbonate used here is generated when the ammonia and water produced during the primary operation are combined with the abiotic carbon dioxide produced during fermentation from the neutralization of the acids. More ammonium bicarbonate is produced here than is needed for the process. The additional ammonium bicarbonate is a product which can be sold (it is used as a fertilizer). However, for the purposes of this analysis, the ammonium bicarbonate was not considered a product to avoid the considerable complication of allocating environmental cost to different products from a process. All of the environmental costs were attributed to the biofuels as the only product. This assumption was considered valid (and conservative) because of the small volume of ammonium bicarbonate produced compared to the large volume of biofuel produced.

Additionally, several compounds are produced and output to the environment in negligible quantities during anaerobic fermentation, including hydrogen sulfide, mercaptans, amines, butyric acid, and pinenes. These compounds are released with the biotic carbon dioxide. While the quantities of these compounds are negligible from a mass balance perspective, they can generate detectable odors that could have implications. Therefore, they were considered in this Life Cycle Assessment only with regard to odor. A biofilter is used in the process to remove the generation of odor. The amounts of these emissions, and that of carbon dioxide, were obtained from the process researchers (Granda and Holtzapple 2007).

When a pile is digested, the remaining solids are removed by slurrying them. The slurry is dewatered in a filter and the resulting solid waste (about 20% of the original biomass) is a product which was assumed to be used as fuel to power the boiler in the conversion plant. The inputs and outputs for the Pretreatment/Fermentation life stage are detailed in Appendix A.

3.2.4 Primary Operation

The Primary Operation life stage begins with the decompression and ends with the formation of alcohol (Figure 6). The amount of land required for Primary Operation was considered negligible when compared to the amount needed for crop production. First the VFA salt solution (fermentation broth) is dewatered to concentrate the salts using a vapor decompression evaporator. Steam is generated from the boiler and used to strip out non-condensable gases, mainly carbon dioxide. The steam that exits the column during this stage is used to provide heat during the esterification/hydrogenolysis. A biodegradable flocculant (e.g. polyacrylamide) is added to the fermentation broth and the solids are removed and sent back to fermentation. The amount of flocculant used was obtained from process researchers and was not in restricted supply (Granda and Holtzapple 2007). The amount of water needed was also obtained from the process researchers, as well as the amount that is eventually sent to waste water treatment (Granda and Holtzapple 2007).

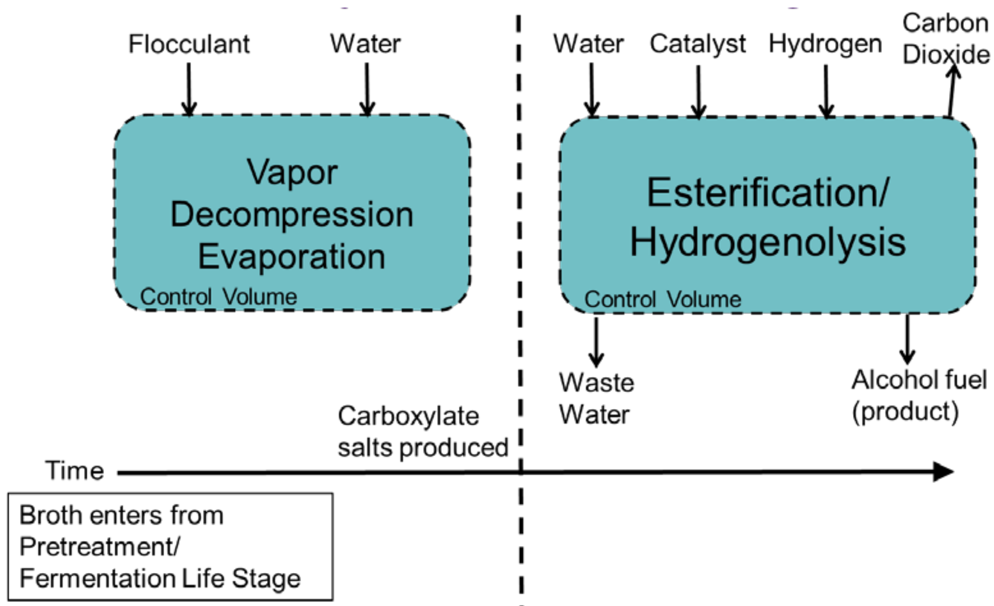

Figure 6. Primary Operation Life Stage Process Flow

The carboxylate salts from the fermentation process then go through the esterification/hydrogenolysis process. The salts are converted to esters by reacting with high molecular weight alcohols. Then the esters are converted to primary alcohols by hydrogenolysis, which uses a Raney Nickel catalyst and hydrogen. The amount of catalyst and hydrogen input from the environment was obtained from process researchers and is not in restricted supply (Granda and Holtzapple 2007). The final alcohols are the biofuels, which are output to the environment. This quantity was also obtained from process researchers (Granda and Holtzapple 2007). The inputs and outputs for the Primary Operation life stage are detailed in Appendix A.

3.2.5 Recycle/Reuse/Disposal

The MixAlco process has been optimized to efficiently recycle and reuse many elements throughout the process. Most of the water is recycled and the thermal control makes use of the heat generated as part of the process. The remaining water is sent to a water treatment facility. The undigested solids remaining after fermentation (about 20% of the original biomass) were assumed to be used as a fuel for the boiler in the process.

3.3 Life Cycle Impact Assessment

To the degree possible the Life Cycle Impact Assessment was performed according to the requirements in ISO 14044 (International Standards Organization 2006b). The Impact Assessment was designed to connect the life cycle inventory data to the potential environmental damages (Jolliet et al. 2004). The purpose of the Impact Assessment was to understand and characterize the significance of the potential environmental impacts of the process (Guinee 1992; Weitz et al. 1998).

The LCIA steps include: 1) selection of impact categories, 2) assignment of Inventory Analysis data to impact categories, and 3) calculation of contribution from each environmental intervention identified in the Inventory Analysis using characterization models (Figure 7).

A mid-point method as suggested by Jolliet et al. (2004) and Guinee (2001) was used in this research, where the impact categories are defined at a mid-point (i.e. ecological toxicity potential) instead of at the end point (i.e. damage to the ecology).

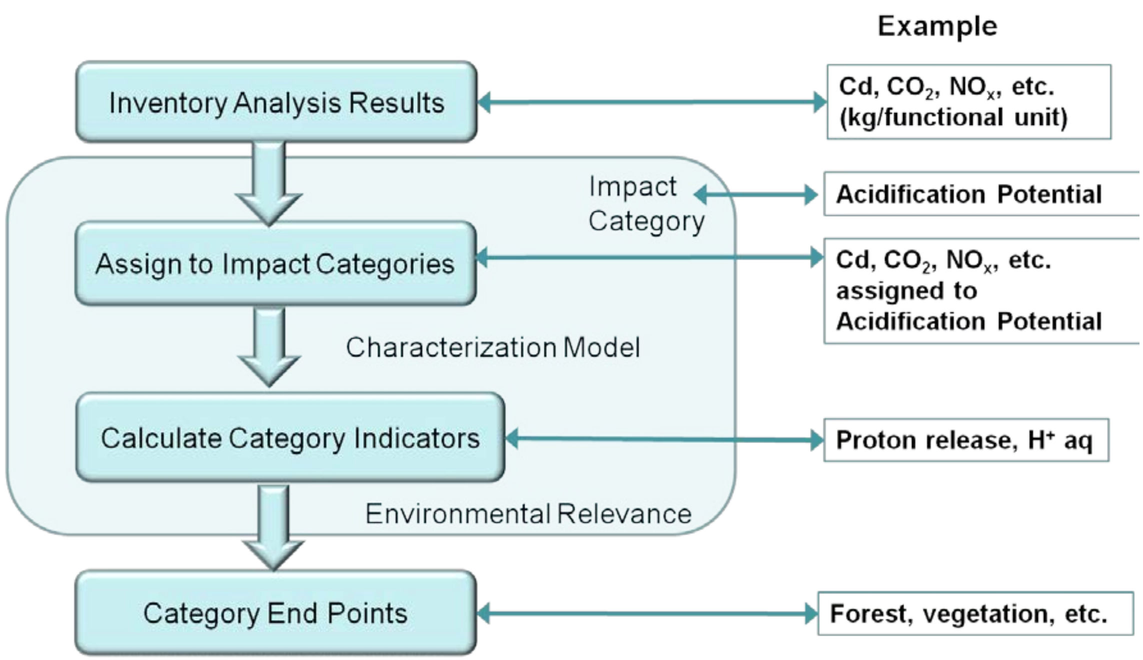

Figure 7. Life Cycle Impact Assessment Procedure (Guinee 2001)

Von Blottnitz and Curran (2007) gave a list of the eight most commonly used impact categories in their review of Life Cycle Assessments for bioethanol. These categories were considered appropriate for this analysis and the use of them allowed for comparisons. These impact categories include: Acidification Potential, Climate Change Potential, Ecological Toxicity Potential, Eutrophication Potential, Human Toxicity Potential, Photochemical Ozone Creation Potential, Stratospheric Ozone Depletion Potential, and Natural Resource Depletion Potential. These categories also correlated directly to the basic list of best available practice category indicators and characterization models selected by the SETAC Working Group on Impact Assessment (Jolliet et al. 2004).

The next step in the Impact Assessment is characterization, where the inputs and outputs identified in the Inventory Analysis were assigned qualitatively to the impact categories. These assignments are also sometimes known as classification. Next, the environmental intervention data that was assigned to a particular impact category was quantified in terms of a common unit for that category, using a characterization model. For this dissertation, the baseline characterization models developed by Guinee (2001) were used for all impact categories. The selection of these models was based on ISO recommended criteria (International Standards Organization 2006a; International Standards Organization 2006b) to maximize accuracy and relevancy within practical modeling limits.

Characterization models are designed to calculate a value known as a category indicator that is a quantifiable representation of an impact category (Equation 1). The model uses characterization factors that are an expression of a particular environmental intervention (emission) in terms of a common unit. The potential impacts of different emissions are assigned a characterization factor (e.g. Climate Change Potential), which allows comparison between different interventions (e.g. greenhouse gasses). The characterization factor is generally expressed as a ratio between the increased effect (e.g. infrared adsorption) due to the instantaneous intervention (e.g. emission) of 1 kg of the substance (i.e. greenhouse gas) and the amount due to an equal intervention (e.g. emission) of a standard substance (e.g. carbon dioxide). These factors are multiplied by the quantity of the intervention (e.g. emission) (Equation 1):

$$\boldsymbol{Impact_{cat} = \sum_i characterization\ factor_{cat,i} \times m_i} \qquad \text{(Equation 1)}$$

where $Impact_{cat}$ is the category indicator, i is the environmental intervention associated with that category, $characterization\ factor_{cat,i}$ is a measure of impact for each environmental intervention, i and category, cat and m_i is the quantity of the environmental intervention (e.g. emission, resource used).

3.3.1 Acidification Potential

Pollutants that cause acidification can impact several different environmental media including groundwater, surface water, soil, and biological organisms. Examples of effects range from death of fish in a freshwater stream to crumbling buildings in a large city. Major pollutants associated with acidification include sulfur dioxide, nitrogen oxides, and ammonia. For this research, emissions of nitrogen oxides and ammonia were applied to this category, with the primary contributor being ammonia resulting from the applied fertilizer. The areas of protection for the acidification category included the natural and man-made environments, human health and natural resources. The characterization model used for this category is given in Equation 2:

$$\boldsymbol{Acidification} = \sum_{\boldsymbol{i}} \boldsymbol{AP_i} \times \boldsymbol{m_i} \qquad \text{(Equation 2)}$$

where *Acidification* is the category indicator (kg SO_2 equivalents), i is the substance released into the environment, AP_i is the Acidification Potential, which is the characterization factor (kg SO_2 equivalents/kg) for the substance i, and m_i is the quantity of the substance i that was released (kg). The Acidification Potential (AP) characterization factors were taken from Huijbregts et al. (Huijbregts et al. 2000a; Huijbregts et al. 2000b) as recommended by Guinee (2001) for an infinite time horizon and on a global scale. This characterization uses the RAINS-LCA model. This model is based on the RAINS model that is supported by the United National Economic

Commission for Europe (UN/ECE). The results for the AP impact category (Table 4) will be discussed comparatively in the consistency check in the Subsection 3.4.1.

Table 4. Acidification Potential Impact Assessment Results

	AP in kg SO_2 eq/kg	**kg SO_2 eq/yr**	**Life Stage**
Ammonia	1.6	5.02E+04	Resource Provisioning
Nitric Oxide	0.5	6.28E+03	Resource Provisioning
Acidification Potential Impact Total		**5.65E+04**	

3.3.2 Climate Change Potential

The Climate Change Potential (CCP) was defined for the purpose of this analysis as the potential impact of the emissions caused by humans on the heat radiation absorption of the atmosphere. When the radiative forcing (change in the balance between solar radiation entering the atmosphere and the radiation going out from the Earth) is increased, the temperature of the earth's surface increases (global warming or greenhouse effect). For this analysis, the primary emissions contributing to climate change are nitrogen, which was used as a fertilizer, and carbon dioxide resulting from the burning of fossil fuels during crop production and transport. The areas of protection for this category are human health, and the natural and man-made environment. The characterization model used for this category is given in Equation 3:

$$\boldsymbol{Climate\ Change} = \sum_i \boldsymbol{CCP_i} \times \boldsymbol{m_i} \qquad \text{(Equation 3)}$$

where *Climate Change* is the category indicator (kg CO_2 equivalents), *i* is the substance released into the environment, CCP_i is the Climate Change Potential (kg CO2 equivalents/kg), which is the characterization factor for the substance *i,* and m_i is the quantity of the substance *i* that was released (kg). The CCP characterization factors used were those recommended by the Intergovernmental Panel on Climate Change (IPCC) for the time horizon of 100 years (Intergovernmental Panel on Climate Change 1992; Intergovernmental Panel on Climate Change 1997) as recommended by Guinee (2001). This characterization method is widely used for CCP impacts in LCAs. The results for the CCP impact category (Table 5) will be discussed comparatively as part of the consistency check in Subsection 3.4.1.

Table 5. Climate Change Potential Impact Assessment Results

	CCP in kg CO_2 eq	**kg CO_2 eq/yr**	**Life Stage**
Nitrous Oxide	310	6.95E+06	Resource Provisioning
Carbon Dioxide	1	3.63E+06	Resource Provisioning
Carbon Dioxide	1	2.49E+02	Pretreatment/ Fermentation
Climate Change Potential Impact Total		**1.06E+07**	

It should be noted that the impact category is named CCP. However, the characterization factor is often called Global Warming Potential (GWP) and sometimes this term is used interchangeably in literature with CCP.

3.3.3 Ecological Toxicity Potential

This impact category covers the potential impact that toxic substances can have on the aquatic and terrestrial environment. For this analysis, the toxicity entering the environment came from the pesticides/herbicides applied during the production of the biomass crop. The areas of protection for this category are the natural environment and natural resources. The characterization model used for this category is given in Equation 4:

$$\boldsymbol{Freshwater\ Ecological\ Toxicity} = \sum_i \boldsymbol{FAETP_i} \times \boldsymbol{m_i} \qquad \text{(Equation 4)}$$

where *Freshwater Ecological Toxicity* is the category indicator (kg 1,4-dichlorobenzene equivalents), *i* is the substance released into the environment, $FAETP_i$ is the Freshwater Aquatic Ecological Toxicity Potential (kg 1,4-dichlorobenzene equivalents/kg), which is the characterization factor for the substance *i,* and m_i is the quantity of the substance *i* that was released (kg). A similar equation was used for *Terrestrial Ecological Toxicity* using the Terrestrial Ecological Toxicity Potential (TETP) characterization factor. The FAETP and TETP characterization factors were taken from Huijbregts et al. (Huijbregts et al. 2000a; Huijbregts et al. 2000b) as recommended by Guinee (2001) for an infinite time horizon and on a global scale. This model is based on the USES-LCA model that uses the European Union supported model EUSES, and is widely used for LCAs.

The results for the Ecological Toxicity Potential impact category for the freshwater aquatic, and terrestrial media ecosystems (Tables 6 and 7) will be discussed comparatively as part of the consistency check in Subsection 3.4.1.

Table 6. Freshwater Aquatic Ecological Toxicity Potential Impact Assessment Results

	FAETP in kg 1,4-DCB eq/kg	**kg 1,4 DCB eq/yr**	**Life Stage**
Atrazine	5000	6.70E+05	Resource Provisioning
Freshwater Aquatic Impact Potential Total		**6.70E+05**	

Table 7. Terrestrial Ecological Toxicity Potential Impact Assessment Results

	TETP in kg 1,4-DCB eq/kg	**kg 1,4 DCB eq/yr**	**Life Stage**
Atrazine	6.60	8.84E+02	Resource Provisioning
Terrestrial Ecological Toxicity Potential Total		**8.84E+02**	

3.3.4 Eutrophication Potential

High quantities of nutrients released into the environment cause eutrophication. The primary nutrients contributing to eutrophication are phosphorus and nitrogen emissions, usually from fertilizer. Both of these nutrients were used as part of the Resource Provisioning life stage for this analysis. Excessive nutrient enrichment can cause undesirable environmental effects including a shift in species composition, "pollution" of drinking water, and significantly increased biomass production in both aquatic and terrestrial ecosystems. The areas of protection for this category are the natural and man-made environment, and natural resources. The characterization model used for this category is given in Equation 5:

$$\boldsymbol{Eutrophication} = \sum_{i} \boldsymbol{EP_i} \times \boldsymbol{m_i} \qquad \text{(Equation 5)}$$

where *Eutrophication* is the category indicator (kg $\mathrm{PO_4^{3-}}$ equivalents), *i* is the substance released into the environment, EP_i is the Eutrophication Potential (kg $\mathrm{PO_4^{3-}}$ equivalents/kg), which is the characterization factor for the substance *i,* and m_i is the quantity of the substance *i* that was released (kg). The Eutrophication Potential (EP) characterization factors were taken from Heijungs et al. (1992) as recommended by Guinee (2001) for an infinite time horizon and on a global scale. This approach was chosen as the baseline because it is location independent, which is preferable because the medium which an emitted substance will eventually enter is unknown. This characterization model is widely used for EP impacts in LCAs. The results for the EP impact category (Table 8) will be discussed as part of the consistency check in Subsection 3.4.1.

Table 8. Eutrophication Potential Impact Assessment Results

	EP in kg PO_4^{-3} eq	**kg PO_4^{-3} eq/yr**	**Life Stage**
Ammonia	0.35	1.10E+04	Resource Provisioning
Nitric Oxide	0.13	1.63E+03	Resource Provisioning
Nitrogen	0.42	9.80E+03	Resource Provisioning
Phosphorus	3.06	5.60E+04	Resource Provisioning
Eutrophication Potential Impact Total		**7.84E+04**	

3.3.5 Human Toxicity Potential

This impact category covers the potential impact that toxic substances can have on human health. For this analysis, the toxicity was associated with the fertilizers and pesticides/herbicides applied during the growth of the biomass crop. The area of protection for this category is human health. The characterization model used for this category is given in Equation 6:

$$\boldsymbol{Human\ Toxicity} = \sum_{i} \boldsymbol{HTP_i} \times \boldsymbol{m_i} \qquad \text{(Equation 6)}$$

where *Human Toxicity* is the category indicator (kg 1,4-dichlorobenzene equivalents), *i* is the substance released into the environment, HTP_i is the Human Toxicity Potential (kg

1,4-dichlorobenzene equivalents/kg), which is the characterization factor for the substance *i,* and m_i is the quantity of the substance *i* that was released (kg). The Human Toxicity Potential (HTP) characterization factors were taken from Huijbregts et al. (Huijbregts et al. 2000a; Huijbregts et al. 2000b) as recommended by Guinee (2001) for an infinite time horizon and on a global scale. This model is based on the USES-LCA model that uses the European Union supported model EUSES, and is widely used for LCAs. The results for the HTP impact category (Table 9) will be discussed comparatively as part of the consistency check in Subsection 3.4.1.

Table 9. Human Toxicity Potential Impact Assessment Results

	Compartment	**HTP in kg 1,4-DCB eq**	**kg 1,4 DCB eq/yr**	**Life Stage**
Ammonia	air	0.1	3.14E+03	Resource Provisioning
Nitric Oxides	air	1.2	1.51E+04	Resource Provisioning
Atrazine	fresh water	4.6	6.16E+02	Resource Provisioning
Atrazine	agricutural soil	21.0	2.81E+03	Resource Provisioning
Human Toxicity Potential Impact Total			**2.16E+04**	

3.3.6 Photochemical Ozone Creation Potential

This impact category covers the potential impact of the formation of reactive chemicals ozone due to sunlight interacting with certain pollutant in the air. In particular, Volatile Organic Compounds (VOCs) and carbon monoxide (CO) will go through photochemical oxidation in the presence of nitrogen oxides (NO_x) and under the influence of ultraviolet light. For this analysis, there were no VOCs or CO emissions associated with the life stages considered and therefore no impact was seen. The areas of protection for this category are human health, the natural and man-made environment, and natural resources.

The characterization model used for this category is given in Equation 7, for completeness:

$$\boldsymbol{Photo-oxidant\ Formation} = \sum_i \boldsymbol{POCP_i} \times \boldsymbol{m_i} \qquad \text{(Equation 7)}$$

where *Photo-oxidant Formation* is the category indicator (kg ethylene equivalents), *i* is the substance released into the environment, $POCP_i$ is the Photochemical Ozone Creation Potential (kg ethylene equivalents/kg), which is the characterization factor for the substance *i,* and m_i is the quantity of the substance *i* that was released (kg). The Photochemical Ozone Creation Potential (POCP) characterization factors were taken from Derwent et al. (1996), Derwent et al. (1998), Fowler et al. (1999) and Jenkin and Hayman (1999) as recommended by Guinee (2001). This model is based on a widely used and supported trajectory model.

3.3.7 Stratospheric Ozone Depletion Potential

This impact category covers the potential impact of certain emissions causing the thinning of the stratospheric ozone layer resulting in more ultraviolet (B) radiation reaching the earth's surface. The emissions of concern for this impact are Chlorofluorocarbons (CFCs). For this analysis, there are no CFC emissions associated with the life stages considered and thus no impact potential. The areas of protection for this category are human health, the natural and man-made environment, and natural resources. The characterization model used for this category is given in Equation 8, for completeness:

$$\boldsymbol{Ozone\ Depletion} = \sum_i \boldsymbol{ODP_i} \times \boldsymbol{m_i} \qquad \text{(Equation 8)}$$

where *Ozone Depletion* is the category indicator (kg CFC-11 equivalents), *i* is the substance released into the environment, ODP_i is the Ozone Depletion Potential (kg CFC-11 equivalents/kg), which is the characterization factor for the substance *i,* and m_i is the quantity of the substance *i* that was released (kg). The Ozone Depletion Potential (ODP) characterization factors were taken from factors compiled by the World Meteorological Organization (WMO) (World Meteorological Organization 1992; World Meteorological Organization 1995) as recommended by Guinee (2001). This model is supported by the WMO and the United Nations.

3.3.8 Natural Resource Depletion Potential

The category of natural resource depletion potential is more complicated than the previous categories because there is not one agreed upon method for evaluating potential impacts, and there are several different types of natural resources. For this analysis, the natural resources of most interest include energy, land, and water. These three areas will be addressed separately.

3.3.8.1 Energy

In LCAs, the impact potential of the depletion of energy resources (i.e. iron ore, crude oil, natural gas, wind, etc.) is often modeled using the depletion of abiotic resources potential in similar manner to the other categories. For this analysis, the energy resources used are fossil fuel resources from the resource provisioning stage. *There are no other inputs of energy to the analysis due to the assumption that the solid residue from the processing of the biomass, and the heat generated as part of the process are used to generate the energy needed to execute the process.* The characterization model used for this category is given in Equation 9:

$$\boldsymbol{Abiotic\ Depletion} = \sum_i \boldsymbol{ADP_i} \times \boldsymbol{m_i} \qquad \text{(Equation 9)}$$

where *Abiotic Depletion* is the category indicator (kg antimony equivalents), *i* is the substance released into the environment, ADP_i is the Abiotic Depletion Potential (kg antimony equivalents/kg), which is the characterization factor for the substance *i,* and m_i is the quantity of the substance *i* that was released (kg). The Abiotc Depletion Potential (ADP) characterization factors were developed by Heijungs and Guinee (1996) as recommended by Guinee (2001). There is no model currently accepted by an international body, but this model is consistent with others used as part of this analysis. Detailed energy analyses have been performed by various researchers that may provide more insight into energy impacts. Some of these analyses will be discussed as part of the policy evaluation (Section 4). For completeness, the results for the ADP impact category (Table 10) will be discussed comparatively as part of the consistency check in Subsection 3.4.1.

Table 10. Abiotic Depletion Potential Impact Assessment Results

	ADP in kg antimony eq	**kg antimony eq/yr**	**Life Stage**
Fossil Fuel	0.0005	6.54E+03	Resource Provisioning
Abiotic Depletion Potential Impact Total		**6.54E+03**	

3.3.8.2 Land

The potential impact of land use is a relatively new area in LCA Impact Assessment and there is not wide-spread agreement on an approach. The potential impacts are discussed in terms of occupation and transformation. Land occupation is the amount of time the land is unavailable for any other use. This time period includes the amount of time required for the land to return to steady-state (recovery time). Land transformation is simply changing the quality of the land. The occupation and/or transformation of land can lead to three damage endpoints for the land: land competition, loss of biodiversity, loss of ability to support life.

As discussed in the Inventory Analysis, it was assumed that the Bioenergy Sorghum would be grown on lands already being used for agricultural purposes (land not transformed). It was further assumed that the land required for the processing plants was negligible when compared to the amount of land required for the crop production. Only land competition will be considered for this analysis. Loss of biodiversity and the ability to support life are not considered because the land is not transformed. However, all of these factors will be discussed as part of the policy evaluation (Section 4) because in a broader sense, land may certainly be transformed to produce crops for bioenergy.

When land is used for any purpose the use of that land for any other purpose is limited or eliminated, leading to greater human competition for land. Thus, the areas of protection when considering land competition are natural resources and the man-made environment. Some attempts have been made to develop an indicator for land competition consistent with other LCA characterization models. However, there is not yet general agreement on the validity of any of these methods. Current practice is a simple summation of land area used, as shown in Equation 10:

$$\boldsymbol{Land\ Competition} = \sum_i \boldsymbol{U_S} \qquad \text{(Equation 10)}$$

where U_S is the land use of state (or quality) S, that can be attributed to the functional unit. The results for the Land Competition Potential impact category are given in Table 11. These results and some comparisons will be discussed in the Life Cycle Interpretation (Subsection 3.4) and the policy evaluation (Section 4). It should be noted there is active research on-going to incorporate land quality and ecosystem services metrics into LCA (Miller 2009).

Table 11. Land Competition Potential Impact Assessment Results

	Hectares	Life Stage
Crop Land	2.13E+04	Resource Provisioning
Land Competition Potential Impact Total	**2.13E+04**	

3.3.8.3 Water

There is no accepted quantitative method for evaluating the potential impact of water use as part of an LCA. This impact area basically covers the problems caused by groundwater extraction that can lead to lowering the water table and introducing water from one area to another (which can cause a change in natural vegetation) in the least. For this analysis, the largest impact potential with regards to water use is during the resource provisioning life stage. It was assumed that there would be no irrigation of the crops, and the crops are designed to have high drought resistance. Bioenergy Sorghum, which was used in this LCA, is derived from Sorghum. Sorghum is generally considered to have low water requirements, especially given its high yield (Evans and Cohen 2009; Lau et al. 2006). Nevertheless, the use of water by the crops for bioenergy in a broader sense, will most certainly be impactful. Thus, this topic will be discussed as part of the policy evaluation (Section 4).

3.3.9 Environmental Profile

The results of the Impact Assessment are summarized below in the Environmental Profile (Table 12). This profile is for the base case (reference flow) conversion plant capacity of 320,000 dry tonnes of biomass/year, which produces 170 million liters per year fuel (Granda and Holtzapple 2007).

Table 12. Environmental Profile (for one conversion plant producing 170 M liters/yr)

Impact Category	Unit	Value
Acidification Potential	kg SO_2 eq	5.65E+04
Climate Change Potential	kg CO_2 eq	1.06E+07
Ecological Toxicity Potential		
Freshw ater Aquatic	kg 1,2 DCB eq	6.70E+05
Terrestrial	kg 1,2 DCB eq	8.84E+02
Eutrophication Potential	kg PO_4^{3-} eq	7.84E+04
Human Toxicity Potential	kg 1,2 DCB eq	2.16E+04
Photochemical Ozone Creation Potential	kg ethylene eq	N/A
Stratospheiric Ozone Depletion Potential	kg CFC-11 eq	N/A
Natural Resource Depletion Potential		
Abiotic depletion Potential	kg antimony eq	6.54E+03
Land Competition	hectares	8.64E+03

It is difficult to interpret the meaning of the numbers given in the Environmental Profile without making a comparison. To develop a sense of the magnitude of the environmental impact described through this LCA a normalization exercise was undertaken. The ISO defines normalization as “calculation of the magnitude of indicator results relative to reference information (International Standards Organization 2006a).” Normalized indicator results for reference systems of the world and the European Union have been developed using the same general LCA framework, where the sum of all the known environmental interventions associated with the reference system was multiplied by the appropriate characterization factors (Guinee 2001; Sleeswijk et al. 2007). The category indicators were divided by the reference category indicators to generate the normalized values (Table 13).

It is expected that the environmental impact of one cellulosic ethanol plant would be relatively negligible compared to the environmental impact of everything else in the world and even in the European Union. It is interesting that the Freshwater Aquatic Ecological Toxicity impacts are actually detectable when normalized by the World and the European Union. This result is likely due to the lack of readily available data regarding agricultural chemicals that are emitted, leached, runoff, and volatized into the environment. All of these normalized results will be further discussed as part of the policy evaluation in Section 4, and they will be scaled up to values consistent with current US policy goals. Additionally, some useful benchmarking comparisons are performed in Subsection 3.4.1 as part of the consistency check.

3.4 Life Cycle Interpretation

Interpretation is the final phase of the LCA and the purpose is to evaluate the robustness and completeness of the choices made during and the results of the analysis. Based on this evaluation, conclusions are drawn which will become part of the policy evaluation in Section 4.

3.4.1 Consistency Checks

3.4.1.1 Data and Characterization Method Consistency Checks

A consistency check of the data was performed to ensure consistency with data sources, accuracy, age, temporal differences, technology level, and geographical representativeness through use of the Data Pedigree Matrix (see Table 3). The quality of each piece of data gathered as part of the Inventory Analysis is given in Appendix A.

Table 13. Percent in Each Category Normalized by Reference Category Indicators for the World and the European Union

Impact Category	**Units**	**Normalization Factor (World)**	**Normalization Factor (European Union)**	**% Normalized Total (World)**	**% Normalized Total (European Union)**
Acidfication Potential (Sleeswijk et al., 2007)	kg SO_2 eq	3.78E+11	2.84E+10	no measurable impact	no measurable impact
Climate Change Potential (Sleeswijk et al., 2007)	kg CO_2 eq	4.18E+13	5.21E+12	no measurable impact	no measurable impact
Freshwater Aquatic Ecological Toxicity Potential (Sleeswijk et al., 2007)	kg 1,4 DCB eq	3.07E+10	6.03E+09	0.002%	0.011%
Terrestrial Ecological Toxicity Potential (Sleeswijk et al., 2007)	kg 1,4 DCB eq	5.09E+10	6.37E+09	no measurable impact	no measurable impact
Eutrophication Potential (Guinee, 2002)	kg PO_4^{-3} eq	1.29E+11	not available	no measurable impact	not calculated
Human Toxicity Potential (Sleeswijk et al., 2007)	kg 1,4 DCB eq	8.86E+12	2.27E+12	no measurable impact	no measurable impact
Abiotic Resources Depletion Potential (Guinee, 2002)	kg antimony eq	1.57E+11	not available	no measurable impact	not calculated

In general, no significant consistency problems were found in the data gathered for this LCA. The only data that is notably different in quality is the pesticide application rate, which precipitated a sensitivity analysis. A consistency check was also performed as part of the Impact Assessment to ensure that the assumptions made and methods used were consistent with the goal and scope of the LCA. These assumptions and methods were discussed as part of Subsection 3.3.

3.4.1.2 Similar Previous Studies Consistency Checks

Finally, the results of the LCA were compared to results of similar previous studies on related processes or crops. The results of this LCA could not be directly compared to these other studies due to differences in data quality, assumptions, cut-offs, and methods. Nevertheless, they did serve to give a rough (order of magnitude) check for the type of results this LCA should produce. The studies which are presented for comparison used two different functional units. The first was hectares, where the category indicator results for each impact category studied were given in units per hectare-year. The second functional unit that was part of this consistency check was tonnes of biomass, where the category indicator results for each impact category were given per tonnes biomass-year.

Comparison to Studies Using Hectares as the Functional Unit

The Impact Assessment results of two studies (Kaltschmitt et al. 1997; Monti et al. 2009) which used hectares as a functional unit, were considered useful and appropriate for the purpose of checking consistency. An overview of the two studies will be discussed first, followed by a comparison of the results.

The first study is a LCA performed to investigate the environmental impact of bioenergy carriers, including Rape Methyl Ester (RME) and fossil diesel fuel

(Kaltschmitt et al. 1997). This study started with the production of fertilizer and machinery and ended with use of the fuel in cars. However, the data was given in fine enough detail that a good comparison could be made and data starting with the cultivation of the crop and ending with the production of biofuels was separated for comparison. Fertilizer and pesticide/herbicide application rates and emission rates, and distances assumed for the transportation of crop were not given. Nitrogen, phosphorus, potassium, and calcium fertilizers were applied to the rapeseed. Only nitrogen and phosphorus fertilizers were applied to the Bioenergy Sorghum. Also, the process for making biodiesel is different from the MixAlco process for making cellulosic ethanol.

The second study presents a LCA on the agricultural production of several potential energy crops including giant reed, miscanthus, switch grass, cynara, and wheat (Monti et al. 2009). This analysis only covered the life stage associated with crop production (did not go onto conversion to biofuel) and a variety of harvesting techniques were used. The amount of nitrogen fertilizer applied to the crops varied from 70 to 180 kilograms per hectare-year. The amount applied to the Bioenergy Sorghum was assumed to be 84 kilograms per hectare-year. The amount of phosphorous fertilizers applied to the energy crops studied by Monti et al. (2009) varied from 33 to 109 kilograms per hectare-year. The amount applied to Bioenergy Sorghum was assumed to be 57 kilograms per hectare-year. Glyphosate (2.0 - 4.0 kilograms per hectare-year) was the pesticide/herbicide applied to the energy crops, whereas atrazine (0.006 kilograms per hectare-year) was applied to the Bioenergy Sorghum. Finally, the cost of fertilizer production was included in the environmental cost for the energy crops in Monti et al. (2009), which was not included for Bioenergy Sorghum. The contribution for this process was not explicitly given. However, the fertilizer production process typically produces carbon dioxide and sulfur dioxide emissions.

Several impact categories were compared (Table 14) for the fuels and crops in both these studies and Bioenergy Sorghum (the crop and the resulting ethanol product). The CCP for Bioenergy Sorghum ethanol is 37% below the CCP for RME. This difference could be due to the contribution to CCP due to the biodiesel conversion process for RME (there is only a negligible contribution to CCP from the MixAlco process). The CCP for Bioenergy Sorghum ethanol is 25% higher than the CCP for fossil diesel. Fossil diesel is not derived from biomass and therefore there are no nitrous oxide emissions due to fertilization to contribute to the CCP, so it is reasonable for this number to be lower than the biofuels (RME and Bioenergy Sorghum ethanol).

The CCP for Bioenergy Sorghum is lower than the CCP for the all crops (wheat, giant reed, miscanthus, and switchgrass) studied by Monti et al. (2009); Bioenergy Sorghum is 15% lower than switchgrass, which had the lowest CCP in that study. The CCP associated with fertilizer production was included for all the crops studied by Monti et al. (2009) but not included for Bioenergy Sorghum. An estimate of carbon dioxide emissions for fertilizer production is given by St. Claire et al. (2008). If this estimated amount (250 kilograms CO_2 equivalent) is added to the CCP for Bioenergy Sorghum, the result (745 kilograms CO_2 equivalent) is 3% higher than the CCP for Miscanthus, which had the highest CCP of the other crops. This difference is reasonable given that emission rates for the fertilizer are not known for these crops. It should also be noted that there is a variation of 55% among the CCPs for these crops which were part of the same study.

Table 14. Comparison of Impact of Different Fuels and Crops for Several Impact Categories

Impact Category	RME[1]	Fossil Diesel[1]	Wheat[2]	Cynara[2]	Giant Reed[2]	Miscanthus[2]	Switchgrass[2]	Bioenergy Sorghum and Bioenergy Sorghum ethanol
Nitrogen Fertilizer Applied (kg/ha-yr)	unknown	not applicable	180	70	80	90	80	84
Phosphorous Fertilizer Applied (kg/ha-yr)	unknown	not applicable	33	52	109	109	87	57
Climate Change Potential (kg CO_2 eq/ha-yr)	7.90E+02	3.74E+02	1.29E+03	6.45E+02	6.71E+02	7.23E+02	5.81E+02	4.96E+02
Acidification Potetntial (kg SO_2 eq/ha-yr)	not calculated	not calculated	9.36E+00	4.12E+00	3.93E+00	4.12E+00	4.12E+00	2.65E+00
Eutrophication Potential (kg PO_4^{-3} eq/ha-yr)	not calculated	not calculated	4.79E+00	1.87E+00	1.68E+00	1.68E+00	1.44E+00	3.67E+00
Freshwater Ecological Toxicity Potential (kg 1,4 DCB eq/ha-yr)	not calculated	not calculated	1.34E+02	7.64E+01	7.64E+01	7.77E+01	4.96E+01	3.14E+01
Terrestrial Ecological Toxicity Potential (kg 1,4 DCB eq/ha-yr)	not calculated	not calculated	7.35E+00	3.38E+00	3.45E+00	3.68E+00	3.45E+00	4.14E-02
Human Toxicity Potential (kg 1,4 DCB eq/ha-yr)	nolt calculated	not calculated	1.36E+03	7.62E+02	6.80E+02	7.21E+02	4.08E+02	1.01E+00
Abiotic Depletion Potential (kg antimony eq/ha-yr)	not calculated	not calculated	1.10E+01	4.62E+00	4.95E+00	5.39E+00	5.72E+00	3.05E+00
Primary Energy (MJ/ha-yr)	8.03E+03	4.60E+03	not calculated	not calculated	not calculated	not calculated	not calculated	6.35E+03

1. Data from Kaltschmitt et al., 1997
2. Data estimated from Monti et al., 2009

The AP was not calculated for the RME or fossil diesel and thus no comparison was performed with Bioenergy Sorghum ethanol. The AP for Bioenergy Sorghum is 33% lower than the giant reed, which had the lowest AP of the crops studied by Monti et al. (2009). This difference is reasonable given that the cost of fertilizer production is included for the energy crops. This production process typically produces sulfur dioxide emissions, which contribute to AP. In addition, the fertilizer emission rates are not known for these crops. It should also be noted that there is a variation of 58% among the APs for these crops which were part of the same study.

The EP was not calculated for the RME or fossil diesel, and thus no comparison was performed with Bioenergy Sorghum ethanol. The EP for Bioenergy Sorghum is within the range of the EPs for the crops studied by Monti et al. (2009). The Bioenergy Sorghum is 23% lower than the EP for wheat, which has the highest EP of the other crops, and 61% higher than the switchgrass, which has the lowest EP for the other crops. These differences are reasonable given that the emission rates for the fertilizers are unknown. It should also be noted that there is a variation of 70% among the EPs for these crops which were part of the same study.

The Ecological Toxicity Potentials for both freshwater (FAETP) and terrestrial (TETP) were not calculated for the RME or fossil diesel, and thus no comparison was performed with Bioenergy Sorghum ethanol. The FAETP for the Bioenergy Sorghum was 37% lower than the FAETP for switchgrass, which was the lowest in the study by Monti et al. (2009). The TETP was 99% lower than cynara, which was the lowest in the study by Monti et al. (2009). The atrazine (applied to the Bioenergy Sorghum) is 3.5 times more toxic in freshwater, and almost 70 times more toxic to the agricultural soil than the glyphosate (applied to the switchgrass and cynara). However, switchgrass and cynara had pesticide (glyphosate) application rates of 3 kilogram per hectare-year and 5 kilogram per hectare-year, respectively. Bioenergy Sorghum had a pesticide (atrazine) application rate of 0.006 kilogram per hectare-year. Thus, the application rate of the pesticide is 500 times greater for the switchgrass, and 830 times greater for cynara than for the Bioenergy Sorghum. This difference can explain the lower toxicity values for the Bioenergy Sorghum. It should be noted that there is a variation of 63% among the FAETPs, and 54% among the TETPs for crops in the same study.

The situation is similar for the comparison of HTP. The HTP for Bioenergy Sorghum was 99% lower than the HTP for switchgrass, which was the lowest in the study by Monti et al. (2009). The atrazine is 70 times more toxic to humans (in freshwater) than the glyphosate. However, given the differences in the application rates discussed above, the differences seen here are reasonable. Also, the HTP is affected by nitrogen fertilizers. Additionally, the potential differences in emission rates could also be playing a role here. It should be noted that there is a variation of 70% among the HTPs for the crops in the same study.

The ADP was not calculated for RME or fossil diesel, and thus a comparison was not performed with Bioenergy Sorghum ethanol. The ADP for Bioenergy Sorghum is 34% lower than the ADP for cynara, which was the lowest in the study by Monti et al. (2009). This difference in ADP is reasonable given that the energy associated with fertilizer production. It should be noted that there is a variation of 58% among the ADPs for the crops in the same study.

The primary energy used for Bioenergy Sorghum is within the range of values given for RME and fossil diesel in Kaltschmitt et al. (1997); 21% lower than that given for RME and 28% higher than that given for fossil diesel. The primary energy was not calculated for the crops studied by Monti et al. (2009).

Comparison to Studies Using Tonnes Biomass as the Functional Unit

The Impact Assessment results of two studies (Brentrup et al. 2001; Brentrup et al. 2004) which used tonnes biomass as a functional unit, were considered appropriate for the purpose of checking consistency. These two studies proved less useful for comparison than the studies in the previous subsection, primarily because of the choice of tonnes biomass as the functional unit. Using tonnes biomass as the functional unit causes the results to be dependent upon the crop yield (tonnes biomass per hectare). The yield of crops varies significantly, which makes comparisons less accurate than the comparisons for functional units such as energy or hectares. An overview of the two studies will be discussed first, followed by a comparison of the results.

Brentrup et al. (2001) conducted a LCA case study on sugar beet production. The purpose of the study was to apply the life cycle methodology to agricultural production, and thus the analysis only addressed the crop production life stage. The extractable sugar yield was approximately 8 tonnes per hectare in Brentrup et al. (2001) and the Bioenergy Sorghum yield was assumed to be 30 tonnes per hectare for this research. Three different types of nitrogen fertilizer (calcium ammonium nitrate, urea, urea ammonium nitrate) were applied to the sugar beets at 115 kilograms per hectare (active N) and 84 kilograms per hectare (active N) were applied to the Bioenergy Sorghum. In addition, phosphorous fertilizer was applied to the Bioenergy Sorghum, but not to the sugar beets. Finally, the environmental costs of fertilizer and machinery production were included in the analysis of the sugar beets, and the emission rates of the fertilizer were not given.

Brentrup et al. (2004) presents a LCA case study of winter wheat production that was found useful for checking consistency. The purpose of this analysis was the application of the LCA methodology to agricultural production and thus the analysis only covered crop production. The wheat yield was 7 tonnes per hectare for the winter wheat and the Bioenergy Sorghum yield was assumed to be 30 tonnes per hectare. The amount of nitrogen fertilizer applied to the winter wheat was 96 kilograms per hectare compared to 84 kilograms per hectare for the Bioenergy Sorghum. In addition to the nitrogen fertilizer, phosphorus, potassium, and magnesium fertilizers were also applied to the wheat. Only phosphorus fertilizer was applied to the Bioenergy Sorghum in addition to the nitrogen fertilizer. The environmental cost of fertilizer production was included for the wheat but not for the Bioenergy Sorghum. When the data was available, attempts were made to improve accuracy of comparison by only using data for emissions that were considered in both analyses.

Several impact categories and some emissions information were compared for the crops in both these studies and Bioenergy Sorghum (Table 15). Lower impacts in all categories were expected for Bioenergy Sorghum due to the fact that there is more fertilizer being applied to a lower yield crops. For wheat, 13% more nitrogen fertilizer was applied to get 77% lower yield than the Bioenergy Sorghum. For sugar beets, 27% more nitrogen fertilizer was applied to get an average of 74% less yield. To aid in comparison, the CCP for nitrogen fertilizer production was estimated to be 16.6 kilograms CO_2 equivalent per tonnes biomass-year, calculated from data given in (St Clair et al. 2008). The primary energy use for nitrogen fertilizer production has also been estimated to be 308.4 mega joule per tonne biomass-year (Kongshaug 1998).

Estimates for other emissions that could be part of fertilizer production (e.g. SO_2 and NO_x) were not found in forms that could be used for this analysis.

Table 15. Comparison of Impact of Different Crops and the Same Crops with Different Nitrogen Fertilizers for a Few Impact Categories and Emissions

	Sugar Beets with CAN[1]	**Sugar Beets with Urea[2]**	**Sugar Beets with UAN[3]**	**Winter Wheat**	**Bioenergy Sorghum**
Yield (tonnes biomass/ha-yr)	8.49	7.31	7.82	8	30
Nitorgen Fertilizer Application Rate (kg/ha-yr)	115	115	115	96	84
Nitrous Oxide Emissions (kg/ha-yr)	not reported	not reported	not reported	3.56E+00	1.05E+00
Ammonia Emissions (kg/ha-yr)	not reported	not reported	not reported	2.36E+00	1.47E+00
Nitrogen Emissions (kg/ha-yr)	not reported	not reported	not reported	1.00E-02	1.09E+00
Nitrogen Oxides (kg/ha-yr)	not reported	not reported	not reported	4.32E+00	5.89E-01
Phosphorous Emissions (kg/ha-yr)	not included	not included	not included	8.60E-02	8.58E-01
Sulfur Dioxide Emissions (kg/ha-yr)	not reported	not reported	not calculated	2.37E+00	not included
Climate Change Potential (kg CO_2 eq/tonnes biomass-yr)	2.40E+02	2.00E+02	2.35E+02	2.25E+02	3.31E+01
Acidification Potetntial (kg SO_2 eq/tonnes biomass-yr)	2.00E+00	5.00E+00	8.00E+00	1.20E+00	1.77E-01
Primary Energy (MJ/tonnes biomass-yr)	not calculated	not calculated	not calculated	1.20E+04	4.24E+02
1. Calcium Ammonium Nitrate					
2. Urea					
3. Urea Ammonium Nitrate					

Some data for emissions from the wheat production were given in kilogram per hectare-year, which facilitated useful comparisons. Emissions for the Bioenergy Sorghum were lower than that for the wheat for nitrous oxide (71% lower), nitrogen oxide (86% lower), and ammonia (38% lower). However, the nitrogen leaching (99% higher) and phosphorus leaching/runoff (90% higher) were higher for the Bioenergy Sorghum than for the wheat. These differences in emission rates are indicative of differences in assumptions regarding emission rates. Thus, a sensitivity study was performed on these emission rates.

The CCP for Bioenergy Sorghum is 85% lower than the CCP for wheat and sugar beets (on average). If the CCP estimate for fertilizer production is added to the CCP for Bioenergy Sorghum, the revised CCP result (49.7 kilograms CO_2 equivalents per tonnes biomass-year), is 78% lower than the CCP for both wheat and sugar beets (on average). Given the dominance of nitrous oxide in the calculation of CCP, the differences in yield, and the lower nitrous oxide emissions, these results are consistent.

The AP for Bioenergy Sorghum is 85% lower than the AP for wheat, and 96% lower than the AP for sugar beets (on average). Given that ammonia is a strong contributor to AP, it is expected that the AP for Bioenergy Sorghum would be lower than the AP for wheat. In addition to this, sulfur dioxide emissions, which are a strong contributor to AP, were included for fertilizer production in the wheat and sugar beet analyses. In fact, the amount of sulfur dioxide emissions associated with fertilizer production was given for the wheat production. If this amount is added to the AP for wheat, the AP more than doubles. Thus, the Bioenergy Sorghum AP results are reasonable. It should be noted that the variation in AP among the sugar beet results was 75% for the same crop, with yield and fertilizer application rate similar to each other.

The primary energy used for Bioenergy Sorghum production was 65% lower that used for wheat production. If the primary energy estimate for nitrogen fertilizer production is added to the primary energy for Bioenergy Sorghum, the revised result (732.4 mega joules per tonnes biomass-year), is 39% lower than primary energy for wheat. This result is consistent given differences in yield, fertilizer application rate and harvesting practices.

3.4.2 Contribution Analyses

The results of the LCA were also subjected to a contribution analysis, wherein the contribution to the LCA results of various identifiable components and parameters was investigated.

3.4.2.1 Contribution by Life Stages

The results were first considered with respect to the contribution by individual life stages. This analysis proved to be straightforward in that all impact categories are only affected by the Resource Provisioning life stage (first life stage) except for the Climate Change Potential impact category. For this category, the Pretreatment/Fermentation life stage (second life stage) also contributes but its impact is seen to be negligible in comparison to the impact from the Resource Provisioning life stage. Nitrous oxide and carbon dioxide emissions are outputs in the Resource Provisioning life stage and carbon dioxide emissions are output in the Pretreatment/Fermentation life stage. Because the impact of nitrous oxide on the CCP is 310 times greater than that of carbon dioxide (Guinee 2001), it is expected that the Resource Provisioning life stage would dominate this impact category.

3.4.2.2 Contribution by Chemicals

Given that the Resource Provisioning life stage had the highest contribution to the environmental cost, the data was further parsed to examine the contribution of fertilizers and pesticides/herbicides. This analysis revealed that the fertilizer contributed 100% of the impact for the AP and EP categories. Fertilizer also contributed 66% of the impact for the CCP category, with the remainder due to carbon dioxide primarily released by machinery and vehicles during crop planting, harvesting, and transporting (there is also a relatively negligible contribution of carbon dioxide released during the Pretreatment/Fermentation life stage). Fertilizers were also responsible for 84% of the impact on HTP with the remaining 16% coming from pesticides/herbicides. Pesticides/ herbicides were responsible for 100% of the impact for both Ecological Toxicity Potentials (Freshwater Aquatic and Terrestrial).

3.4.3 Sensitivity Analyses

Finally, sensitivity analyses were performed to examine the influence of variations in model choices and the robustness of the results to small changes in data choices. These sensitivity analyses are intended to demonstrate the validity and reliability of the results and aid in drawing conclusions.

3.4.3.1 Sensitivity to Characterization Models

Justification for the characterization models selected for each impact category is given in Subsection 3.3 and represent the best available practice. Alternative characterization models suggested by Guinee (2001) were used for the sensitivity study.

Acidification Potential

The alternative characterization model suggested by Guinee (2001) for AP sensitivity comparison is the same model as was used in the original analysis, but with characterization factors for different regions. The original analysis used average European AP characterization factors. Calculations were performed for the generic AP characterization factors. No appreciable difference was seen in the overall AP. Another suggested method was performing the calculations using appropriate regional data. In this case, the appropriate regional data would be for the United States, but this data does not exist.

Climate Change Potential

The alternative characterization model suggested by Guinee (2001) for sensitivity comparison is the same model as was used in the original analysis but with characterization factors for different time horizons. The original analysis calculated the CCP using a 100 year time horizon. Calculations were performed with characterization factors for the 20 year and 500 year time horizons. No appreciable difference was seen in the overall CCP.

Ecological Toxicity Potential

The alternative characterization model suggested by Guinee (2001) for Ecological Toxicity sensitivity comparison is the same model as was used in the original analysis but with characterization factors for different time horizons. The original analysis used the characterization factors for an infinite time horizon. Calculations were performed with characterization factors at the 20 year and 100 year time horizons. No appreciable difference was seen in the overall FAETP or TETP.

Eutrophication Potential

The alternative characterization model suggested by Guinee (2001) for EP sensitivity comparison is the same model as was used in the original analysis but with characterization factors for appropriate regions. The original analysis used generic EP characterization factors. The appropriate regional data for the alternative approach would be for the United States, but this data does not exist.

Human Toxicity Potential

The alternative characterization model suggested by Guinee (2001) for HTP sensitivity comparison is the same model as was used in the original analysis but using characterization factors from different time horizons. The original analysis used the characterization factors for an infinite time horizon. Calculations were performed using the characterization factors for the 20 year and 100 year time horizons. No appreciable difference was seen in the overall HTP.

Stratospheric Ozone Depletion Potential

Sensitivity not performed because this research does not have any impact in this category.

Photochemical Ozone Creation Potential

The alternative models suggested by Guinee (2001) for the Photochemical Ozone Creation Potential (POCP) are based on the Maximum Incremental Reactivity and the Maximum Ozone Incremental Reactivity for substances. These models do not account for nitrogen in the appropriate forms for the data associated with this research and therefore could not be performed because nitrogen is the only chemical in this research that applies to this impact category.

Abiotic Depletion Potential

The alternative models suggested by Guinee (2001) by for the ADP sensitivity are based on: 1) economic reserves and extraction rates, and 2) ultimate economic reserves only. The data needed to use the models for this analysis does not exist; thus a sensitivity to models was not performed for this impact category.

Land Competition

At this time, no appropriate alternative model exists for sensitivity comparisons.

Observations Regarding Sensitivity to Characterization Models

While change to the characterization models seen here did not have significant impact, gaps in the data and models were noted. The ability of researcher to make assessments at the system level through LCAs could be improved by more complete and accurate data. It is clear that nitrous oxide is a dominant factor in climate change, which will be ever more important if biofuels are implemented on a large scale. There is significant research in modeling climate change for all levels of analysis including LCAs, which should continue to benefit these environmental efforts. Additionally, continued research is needed for characterization models of acidification, eutrophication, and ecological and human toxicity to make them more location and time independent, and to gather appropriate regional US data so that smaller scale LCAs can be accomplished accurately. As biofuels begin to make up a larger portion of the US energy portfolio, the need for characterization of regional US impact data becomes clear.

3.4.3.2 Sensitivity to Data Assumptions and Variations

Discussion of the data gathered for this research is given as part of the Inventory Analysis (Subsection 3.2) and the associated Data Pedigree Matrix is given with the data in Appendix A. To evaluate the sensitivity of the Impact Assessment results to the data and assumptions made regarding the data, sensitivity studies were performed on nitrogen emissions and pesticide/herbicide application rates.

Sensitivity to Fertilizer Emissions

The results of the Impact Assessment revealed nitrogen releases from the application of fertilizers can significantly affect the environmental cost of cellulosic ethanol production. The data for the nitrogen fertilizer application rate was obtained directly from Bioenergy Sorghum developers. The data for the emissions to air, water, and soil were obtained from literature on this topic (Akiyama et al. 2010; Alexander 1985; Bouwman 1996; Bouwman et al. 2002a; Bouwman et al. 2002b; Crutzen et al. 2008; Dalgaard et al. 2006; Sathre et al. 2010; Sharpley A. N. et al. 2003; Smeets et al. 2009; Virkajarvi et al. 2010; Zhao et al. 2009; Zhuang and Wang 2009). Due to the many variations in growing environments, crops, and agricultural practices, a range of values were reported in literature, which were used in this sensitivity analysis. These emission values for nitrous oxide, ammonia, nitrogen, and phosphorous were changed systematically over the ranges, and the results of the Impact Assessment recalculated each time. The percent change in each applicable impact category of a 1% change in the chemical emission is given in Table 16.

A 1% change in the ammonia emissions caused almost a 1% change in the AP, a 0.2% change in EP, and a 0.2% change in HTP. Thus, AP was sensitive to ammonia emissions. The CCP changed almost 1% for every 1% change in nitrous oxide emissions, demonstrating that CCP was sensitive to nitrous oxide. A 1% change in phosphorus emissions caused a 0.8% change in EP, demonstrating that EP is sensitive to changes in phosphorus emissions. Finally, a 1% change in nitrogen emissions caused a 0.1% change in EP. These results indicate that AP, CCP, and EP were sensitive to changes in these emissions. Thus, it is important that the fertilizer application rates and subsequent emission rates be accurate and that assumptions regarding these be documented.

Table 16. Percent Change in Impact Potential Caused by a 1% Increase in Emission Rate

	Acidification Potential % Change	Climate Change Potential % Change	Eutrophication Potential % Percent Change	Human Toxicity Potential % Change
Nitrous Oxide	does not contribute	0.9	does not contribute	does not contribute
Ammonia	0.9	does not contribute	0.2	0.2
Nitrogen	does not contribute	does not contribute	0.1	does not contribute
Phosphorus	does not contribute	does not contribute	0.8	does not contribute

These sensitivities were studied further by investigating worst case scenarios. The range found in literature for nitrous oxide emission to the air from the application of fertilizer was from 0.1% to 5.0% of the applied nitrogen (Bouwman 1996; Chirinda et al. 2010; Crutzen et al. 2008; Gopalakrishnan et al. 2009; Sathre et al. 2010). This was a comparatively large range, which was indicative of uncertainty in the data. A nitrous oxide emission rate of 1.25% of applied nitrogen was assumed for Bioenergy Sorghum based on the recommendations by the IPCC (Intergovernmental Panel on Climate Change 2007c). When the Impact Assessment calculations were performed for the worst case assumption of a nitrous oxide emission rate of 5.0% of the applied nitrogen, the impact for the CCP was increased by 67% (over the results for the assumed value). These results further indicate that CCP is sensitive to nitrous oxide emissions. In this case, although literature does give a range, the assumption used in this research was justified by the recommendation of the IPCC. However, this sensitivity points to the need for accurate data regarding nitrogen fertilizer application and emissions.

The range found in literature for ammonia emissions to air from application of fertilizer was from 1.0% to 2.5% of the applied nitrogen (Zhao et al. 2009; Zhuang and Wang 2009). This range was comparatively small, but still indicative of some uncertainty in the data. The value used in this research was the middle of this range (1.75%) because no value was found for sorghum or that was supported in general by a recognized organization. When the Impact Assessment calculations were performed for the worst case assumption of an ammonia emission of 2.5% of the applied nitrogen, the the AP increased by 38% (over the results for the assumed value), the EP increased by 5% (over the assumed value) and HTP increased 6% (over the assumed value). These results further exemplify that there is some sensitivity to changes in ammonia emissions which affects AP. Increasing the accuracy of databases on nitrogen fertilizer application and emissions, as discussed previously for nitrous oxide will also benefit these impact categories.

The range found in literature for nitrogen emission to water from the application of fertilizer was from 1.0% to 1.6% (Petronella et al. 2009; Zhao et al. 2009) of the applied nitrogen. This range is comparatively small and indicative of little uncertainty in the data. The value used in this research was the middle of this range, 1.3% because no value was found for sorghum or that was supported by a recognized organization. When the Impact Assessment calculations were performed for the worst case assumption of a nitrogen emission of 1.6% of the applied nitrogen, the impact for the EP is increased by 2.3% (over the results for the assumed value). These results indicate that there is little sensitivity to changes in nitrogen emission which impacts the EP.

The range found in literature for phosphorus leaching/runoff was between 1.0 and 2.0% of the applied phosphorous (Sharpley A. N. et al. 2003). The value used in this research was 1.5% of the applied phosphorus, which is the middle of the range. This amount was used because a value could not be found for sorghum or that was accepted by a recognized organization. When the Impact Assessment calculations were performed for the worst case assumption of 2% of the applied phosphorous, the impact for the EP was increased by 24%. These results indicate that there is some sensitivity to changes in phosphorus emissions. Increasing the accuracy of databases on fertilizer application and emissions, as discussed above, will also benefit EP.

Sensitivity to Pesticides and Herbicides

Quantitatively accurate data was difficult to find for the application of pesticides and herbicides in general. The type of pesticide used, atrazine, was obtained from the Bioenergy Sorghum researchers. The application rate information was found in a database created and maintained by an environmental organization, Pesticide Action Network, which is not state or federally regulated or internationally supported. This database contains the application rates for a large number of pesticides and herbicides in the state of California. The data used for this analysis was for forage sorghum (Pesticide Action Network North America 2010). The Impact Assessment revealed that the pesticides/herbicides were significant contributors to the environmental impact of some categories, and thus, a sensitivity analysis was performed. The ranges used for this sensitivity study were from the same database. The range used for atrazine application rate was 0.84 kilograms per hectare to 3.21 kilograms per hectare. This range was comparatively large and indicative of uncertainty in the data. The application rate was varied systematically over this range and the results of each applicable impact category recalculated.

The percent change in the Ecological Toxicity Potentials to a 1% change in the atrazine application rate was 1%. Thus, the FAETP and the TETP were sensitive to assumptions regarding the application rate of pesticides and herbicides. Clearly, more definitive data about application rates and emissions of pesticides/herbicides is desirable and would improve the accuracy of these results and any other environmental analysis. It would also allow more pesticides/herbicides to be evaluated, which is important due to the wide variety of chemical that are used on crops.

The Impact Assessment calculations were also performed for the worst case assumptions of 3.21 kilograms per hectare for the application rate of atrazine. The Ecological Toxicity Potentials increased by 187%, and the Human Toxicity Potential increased by 30% over the assumed value. These results further indicate that the FAETP and the TETP are sensitive to the application rate of the pesticide/herbicide. The assumptions used in this research are reasonable (average application rates for Forage Sorghum grown in California) given input from Bioenergy Sorghum researchers.

In summary, the results of the sensitivity studies performed in this subsection indicate that while the assumptions made in this analysis are reasonable, there are significant sensitivities to some of the assumptions regarding the inputs and outputs, particularly of fertilizers, and pesticides/.herbicides. Thus, it would be useful for excellent data to be gathered, documented and made available, regarding the application and emission rates of these chemicals. In addition, these sensitivity studies provided significant insight that these emissions have the potential to have significant impact if used on a large scale. These insights will be used and further explored in the policy evaluation (Section 4) when agricultural practices are investigated. Recommended future studies will also be discussed in Sections 4 and 5.

4. POLICY EVALUATION

The environmental evaluation discussed in Section 3 is an important component of the research to investigate cellulosic ethanol as a potential partial alternative to fossil fuels. This research is continued with a policy evaluation. Potential policy elements are discussed in this section that could become part of a policy portfolio to support cellulosic ethanol. These policy portfolio alternatives are evaluated for their advantages and disadvantages and how they could be received by various constituencies. This effort results in a set of policy recommendations that take into consideration the environmental concerns raised by the LCA in Section 3.

4.1 Current Policy Overview

Technical experts and policy makers generally agree that it is important for the US to transition away from dependence on nonrenewable fuels (USDA, 2010). The current energy infrastructure uses primarily oil and gas and facilitates at least near term reliance on fossil fuels. Additionally, the cost of fossil fuels is relatively low, resulting in little natural economic incentive for the development and production of alternative fuels. Policy changes are needed to ensure that renewable resources are positioned to play a major role in satisfying the global or US energy demands, especially liquid fuel for vehicles. A thoughtful, comprehensive, policy portfolio can serve to encourage and support the companies and organizations involved in the biofuels research, development and commercialization activities and allow alternative energy to grow and thrive in the US.

4.1.1 Current Federal Policy

The Energy Policy Conservation Act of 1975 added the Improving Automotive Efficiency to the Motor Vehicle Information and Cost Savings Act and established

Corporate Average Fuel Economy (CAFE) standards for light duty vehicles (passenger cars and light trucks) through 2016. This Act was originally passed in response to the Arab oil embargo in 1973 and 1974. CAFE credits are given for vehicles that run on E85.

In October 2010, the Environmental Protection Agency (EPA) and the Department of Transportation (DOT) (National Highway Traffic Safety Administration 2010) announced they would develop tougher greenhouse gas and fuel economy standards for passenger cars and light trucks built in model years 2017 through 2025. The goal is to announce the new rules within a year. These organizations also proposed a similar program to apply to medium and heavy-duty vehicles. This additional rule is seen as needed due to the fact that medium and heavy-duty vehicles are the fastest growing contributor to greenhouse gas emissions. The proposed rule is currently in public comment period.

The Clean Air Act Amendments of 1990 established a requirement for gasoline sold in certain affected areas during the winter months to contain 2.7 percent oxygen by weight to reduce carbon monoxide (CO) emissions from vehicles. Ethanol is the oxygenate most often used to meet this requirement. The Clean Air Act Amendments of 1995 established a requirement that the cities with the worst air pollution problems use re-formulated gasoline (RFG). RFG is a gas blended to burn cleaner by reducing smog-forming and toxic emissions that pollute the air for breathing and cause ground level ozone creation. The law requires the RFG to contain 2 percent oxygen by weight. Methyl tertiary butyl ether (MTBE) and ethanol are the two most commonly used substances for this purpose; however, oil companies can decide which substance to use to meet the requirement.

On December 19, 2007 Congress signed the Energy Independence and Security Act (EISA) of 2007 into law (Energy Independence and Security Act 2007). This policy amended the Renewable Fuel Standards (RFS) that was signed into law in 2005. The RFS set a mandatory blend level for renewable fuels and established a greenhouse gas reduction criteria. The RFS policy is designed to develop a market for alternative transportation fuels. It is considered a flexible market-based policy which can correct market issues such as the existing fossil fuel infrastructure, risk associated with developing alternative fuel technologies, and consumer cultural bias against or ignorance about alternative fuels (Couture and Cory 2009). The RFS required volumes are given in Table 17. The RFS also allows credit trading where refiners can use less than the required biofuel amount if they purchase credits from suppliers who choose to use more than the required amount. Conventional biofuels are those derived from corn starch (corn ethanol). Advanced biofuels are those that cut greenhouse gas emission by at least 50%, which includes cellulosic ethanol, ethanol derived from wastes, biodiesel, and biobutanol. Cellulosic biofuels are those derived from cellulose, lignocellulose, or hemicellulose. Biomass-based diesel is a diesel fuel substitute produced form non-petroleum renewable resources. Undifferentiated advanced biofuels are biofuels other than corn ethanol. This category can also include co-processed renewable diesel.

The RFS policy is designed to phase in an increase in the amount of biofuel other than corn ethanol such that a smaller percentage of corn ethanol is being used over time. This gradual downsizing is due to recognition of the ethical and natural resource depletion concerns associated with corn ethanol production.

Table 17. Federal Renewable Fuel Standards (as given in EISA, Section 202 - not showing recent changes)

Renewable Fuel Standards in Billion Liters						
Year	Renewable Biofuel	Advanced Biofuel	Cellulosic Biofuel	Biomass-Based Diesel	Undifferen-tiated Advanced Biofuel	Total Renewable Fuel Standard
2008	34.1	-	-	-	-	34.1
2009	39.7	2.3	-	2.3	0.4	44.7
2010	45.4	3.6	0.5	2.5	0.8	52.7
2011	47.7	5.1	0.9	3.0	1.1	57.9
2012	50.0	7.6	1.9	3.8	1.9	65.1
2013	52.2	10.4	3.8	3.8	6.6	76.8
2014	54.5	14.2	6.6	3.8	7.6	86.7
2015	56.8	20.8	11.4	3.8	9.5	102.2
2016	56.8	27.4	16.1	3.8	11.4	115.4
2017	56.8	34.1	20.8	3.8	13.2	128.7
2018	56.8	41.6	26.5	3.8	15.1	143.8
2019	56.8	49.2	32.2	3.8	17.0	159.0
2020	56.8	56.8	39.7	3.8	17.0	174.1
2021	56.8	68.1	51.1	3.8	17.0	196.8
2022	56.8	79.5	60.6	3.8	18.9	219.5

The EISA included a waiver that authorized the EPA administrator to lower the cellulosic biofuels requirement if the minimum volume requirement is not met. In 2010 the RFS cellulosic ethanol requirement which was set at 378.5 million liters (100 million gallons), was lowered to 24.6 million liters (6.5 million gallons), and the 2011 requirement was lowered from 946 million liters (250 million gallons) to 64.7 million liters (17.1 million gallons). The reason given for this change is that the cellulosic ethanol technology still lacks proper technical development to produce at this scale (Environmental Protection Agency 2010).

The EISA also authorizes funding for grants in biofuels research. First, there is $500 million in grants for the production of advanced biofuels that have at least an 80 percent reduction in the lifecycle greenhouse gas emissions relative to current fuels (Energy Independence and Security Act 2007), Section 207. Also, $25 million is slated for research and development and commercial application of biofuels production in states with low rates of ethanol and cellulosic ethanol production (Energy Independence and Security Act 2007), Section 223 in FY 2008 – FY 2010. Finally, there is $200 million for the installation of refueling infrastructure for E-85 (Energy Independence and Security Act 2007), Section 244 in FY 2008 – FY 2014.

Title IX of the 2008 Farm Bill contains several renewable energy provisions. The Biorefinery Assistance Program (Food Conservation and Energy Act 2008), Section 9003 provides loan guarantees for the development, construction and retrofitting of commercial-scale biorefineries, and grants to help pay for the development and construction of demonstration-scale biorefineries. The Bioenergy Program for Advanced Biofuels (Food Conservation and Energy Act 2008), Section 9005 provides support for eligible agricultural producers to encourage the expansion of the production of advanced biofuels. The Biodiesel Fuel Education Program (Food Conservation and Energy Act 2008), Section 9006 provides grants to educate government and private entities that operate fleets and the public in general about the benefits of biodiesel. The Biomass Research and Development Initiative (Food Conservation and Energy Act 2008), Section 9008 provides grants and other financial assistance for research, development and demonstration of biofuels production technology. The Feedstock Flexibility Program for Bioenergy Producers (Food Conservation and Energy Act 2008) Section 9010, subsidizes the use of sugar for the production of ethanol. The Biomass

Crop Assistance Program in the (Food Conservation and Energy Act 2008) Section 9011, supports the production of crops for conversion to bioenergy. The Forest Biomass for Energy program (Food Conservation and Energy Act 2008) Section 9012, authorizes the Forest Service to perform a research and development program on the use of forest biomass for energy.

4.1.2 Current State Policies

In the US, states have significant authority in energy policy and they play an important role in the development and commercialization of new energy technologies. States are also responsible for development of the fueling infrastructure for alternative fuels. The federal government encourages the development of biofuels on a state level through the State Energy Program (SEP), which is a federally funded (DOE), state-based program that provides resources directly to the States for allocation by them for energy efficiency and renewable energy (National Association of State Energy Officials 2011).

Many states have production incentive programs to encourage biofuels production. Several states have grant programs to support infrastructure development for biofuels. A few states have also implemented a state-level RFS to encourage advanced biofuels production in their state. Hawaii and Minnesota started with the RFS even before the federal RFS was implemented in 2006. After the federal RFS was implemented, other states implemented RFSs. State-level policies which affect alternative fuel production are given in Table 18 by state.

It is hard to find a trend in this spread of policies. However, 28 of the 50 states have infrastructure programs to help develop infrastructure for the production and deployment of biofuels, 20 have producer incentive programs to help encourage

Table 18. State-Level Policies that Affect Alternative Fuel Production (modified from National Association of State Energy Officials 2011)

State-Level Policies that Affect Alternative Fuel Production									
State	Producer Incentive Programs	Infra-structure Incentive Programs	State-level RFS	State Fleet Fuel Purchase/ Use Requirement	State	Producer Incentive Programs	Infra-structure Incentive Programs	State-level RFS	State Fleet Fuel Purchase/ Use Requirement
Alabama	x	x			Montana	x		x	
Alaska		x			Nebraska				x
Arizona					Nevada				
Arkansas	x				New Hampshire				
California					New Jersey		x		
Colorado		x			New Mexico				
Connecticutt					New York		x		x
Delaware					North Carolina	x	x		
District of Columbia					North Dakota	x	x		
Florida		x	x		Ohio		x		
Georgia					Oklahoma	x	x		
Hawaii	x	x	x		Oregon		x	x	x(Portland Only)
Idaho		x			Pennsyvania			x	
Illinois		x			Rhode Island		x		
Indiana	x	x		x	Sounth Carolina	x	x		
Iowa		x	x	x	South Dakota	x	x		
Kansas	x	x		x	Tennessee				
Kentucky	x			x	Texas	x			
Louisiana		x	x		Utah		x		
Maine	x	x			Vermont				
Maryland	x				Virginia	x			x
Massachusetts					Washington		x	x	x
Michigan		x			West Virginia				
Minnesota	x	x	x	x	Wisconsin		x		
Mississippi	x				Wyoming	x			
Missouri	x	x	x	x					

investment in the production of biofuels, 11 have some requirements for their state fleets to use biofuels, and 10 states have augmented the federal RFS with a state-level RFS. Twelve states have no state programs and rely on the federal programs alone, and thus 38 states have some type of biofuels program.

4.2 Impacts of Scaling Up

This section generalizes the impacts noted in Section 3 from the MixAlco process using Bioenergy Sorghum, to cellulosic ethanol on a scale that is consistent with the goals of current federal energy policy as discussed in Subsection 4.1. In addition to these environmental impacts, economic, social, and cultural impacts will be discussed.

In 2009, 392 billion liters of motor gasoline was consumed, with 66% (257 billion liters) of that being conventional gasoline (not reformulated with oxygenates); 42 billion liters of ethanol were produced and consumed, which is about 1% of the total US energy consumption. No cellulosic ethanol large scale commercial plants have been built; zero gallons of cellulosic ethanol were commercially produced in 2009. Thus, a significant increase in the production of cellulosic biomass will be required to meet the standards required by the RFS. For perspective, consider the process examined in Section 3, the MixAlco process, which produced 171 million liters per year of cellulosic ethanol from 320,000 dry tonnes of Bioenergy Sorghum. Approximately 21.3 thousand hectares per year of land were required to produce this quantity of biomass. If the cellulosic ethanol required to be produced in the RFS by 2022 (61 billion liters) is assumed to be produced by a process such as the MixAlco process and using a bioenergy crop such as Bioenergy Sorghum, then about 748 thousand hectares of land for production of the biomass and about 350 cellulosic ethanol processing plants would be required to meet the RFS for just cellulosic ethanol. The impacts given in the

Environmental Profile (Table 13) were scaled up to RFS levels for 2022 and normalized by the reference category indicators for the world (Table 19).

These results indicate that while the overall environmental impact may not be dramatic, it is evident on a global scale in most categories. Again the normalized FAETP is disproportionately large. The cause of this difference is likely issues with the data for toxicity in the normalized value. The FAETP for cellulosic ethanol was seen to be reasonable in the consistency check. The category that is most often the environmental focus is CCP. The normalized CCP does show some impact when enough crop is produced to meet the RFP for cellulosic ethanol. The normalized EP impact shows that a large increase in fertilizer use, such as will be required for the RFS, could have a measurable impact on EP, and a smaller one on AP.

4.2.1 Economic Impacts

A clear cut path has not been defined for establishing energy independence without placing an additional burden on the already beleaguered US economy. Energy is important to the economy from the standpoint of consumption, production, and trade. Making biofuels economically competitive with petroleum appears to be a key factor. The World Business Council for Sustainable Development (WBCSD) suggests "encouraging the development and deployment of leading-edge technologies through partnerships and incentives and an approach to mitigate the long-term market risk and deliver secure benefits for large-scale, low-carbon, new technology projects (World Business Council for Economic Development 2006)."

Many biofuels technology leaders believe that cellulosic ethanol technology is ready, but the economic recession has stymied the necessary financing to build the large-scale commercial plants, costing approximately $100M to $600M (Aden A. et al. 2002; Port O.

2005; Vaughan V. 2011). Investment in energy, both fossil and alternative, has fallen worldwide due to falling demand and lower cash flow (International Energy Agency 2009). “Although the situation is uncertain, EIA’s present view of the projected rates of technology development and market penetration of cellulosic biofuel technologies suggests that available quantities of cellulosic biofuels will be insufficient to meet the RFS targets for cellulosic biofuels before 2022 (Energy Information Administration 2011).” Nevertheless, most believe that the RFS mandates for required quantities of cellulosic ethanol at the levels originally dictated by the EISA are needed to create the demand that will encourage oil companies (and others) to invest in cellulosic ethanol.

Table 19. Percent Impact in Each Category Normalized by Reference Category Indicators for the World When Scaled to RFS Amounts for 2022

Impact Category	**Units**	**Normalization Factor (World)**	**% Normalized Total (World) for 136 billion liters of cellulosic ethanol**
Acification Potential (Sleeswijk et al., 2007)	kg SO_2 eq	3.78E+11	0.012%
Climate Change Potential (Sleeswijk et al., 2007)	kg CO_2 eq	4.18E+13	0.020%
Freshwater Aquatic Ecological Toxicity Potential (Sleeswijk et al., 2007)	kg 1,4 DCB eq	3.07E+10	1.746%
Terrestrial Ecological Toxicity Potential (Sleeswijk et al., 2007)	kg 1,4 DCB eq	5.09E+10	0.001%
Eutrophication Potential (Guinee, 2002)	kg PO_4^{-3} eq	1.29E+11	0.049%
Human Toxicity Potential (Sleeswijk et al., 2007)	kg 1,4 DCB eq	8.86E+12	no measurable impact
Abiotic Resources Depletion Potential (Guinee, 2002)	kg antimony eq	1.57E+11	0.003%

A study conducted by the USDA indicated that if the production technology advances and petroleum prices rise (as projected by the DOE), the US economy would benefit from the RFS through higher wages and income, and lower import prices. The recent lowering of the RFS requirements will no doubt alter these results as the demand for biofuels is decreased.

It should be noted that many companies are at least dabbling in alternative fuels. Shell recently partnered with Brazilian ethanol producer Cosan and has previously partnered with Codexis and Iogen (Renewable Energy World 2010). Other partnerships include, Petrobas with KL Energy Corporation, Chevron with Mascoma, and Exxon Mobile with Synthetic Genomics. Car companies have also begun to invest in ethanol technologies; General Motors made a large investment in Coskata (Blanco 2010). All of these investments appear to be largely motivated by the RFS mandates.

4.2.2 Social and Cultural Impacts

If the production of biofuels is scaled up to the current policy goals, a significant portion of the fuel source will come from biomass production. Because cellulosic ethanol has not gone to large scale production, the best existing example of the social and cultural impacts is corn ethanol. Low and Isserman (2008), who focused primarily on corn ethanol, pointed out some potential short falls of biofuels production, including that its long term evolution is uncertain. They also discuss the significantly increased need for water, which is a commodity greatly valued by the agricultural community. New ethanol plants can also increase the truck traffic, taxing rural infrastructures. Swenson (2008) looked at the economic impact of corn ethanol on rural communities in Iowa and concluded that ethanol plants provided jobs to rural areas, created manufacturing activity that stimulated local economies, and raised the price of corn. These effects are considered positive from the perspective of farming communities.

However, the rising price of corn, while beneficial to the corn farmer, has given rise to strenuous debate about the impact of ethanol on food and feed supplies. There are those who claim we can do both (Sneller and Durante 2008). Nevertheless, the competition between food and fuel markets is an ethical, economic, and a political concern on a global scale (Hill et al. 2006; Perlack et al. 2005; Schmer et al. 2008; Tilman et al. 2006). Since 2005, when the RFS was signed into law, the amount of corn used for ethanol has increased from 16 percent to 21 percent. Pimentel et al. (2009) point out that “Nearly 60% of the humans in the world are currently malnourished, so the need for grains and other basic foods is critical.” Many feel that growing food crops for energy is a misuse of resources that could be used to produce food for human consumption. In addition, using corn for production of ethanol has been shown to increase the prices of beef, chicken, pork, eggs, breads, cereals, and milk (Pimentel et al. 2009).

It is clear that a non-food/feed crop will have less impact; nevertheless, even if a food/feed crop is not used, any crop will compete with food/feed crops for natural resources.

4.2.3 Energy Impacts

The amount of energy used to produce cellulosic ethanol is an important consideration. The LCA performed on the MixAlco process using Bioenergy Sorghum (Section 3) considers energy use as a natural resource that is depleted by use (fossil fuel use). This analysis did not indicate the use of fossil fuels was a significant concern. However, because there is not general agreement about the best approach for addressing energy in LCAs, especially when evaluating a process for making fuel, it is prudent to look at additional energy analyses. Several investigations explored whether the energy derived from the biomass will yield more energy than the energy used in growing, harvesting, and converting it (Cleveland 2005; Minnesota Department of Agriculture 2009; Patzek et al. 2005; Shapouri et al. 2003; Shapouri and McAloon 2001; Sheehan et al. 1998; Visalli 2006).

Regarding the comparison of corn ethanol to cellulosic ethanol, Farrell et al. (2006) reported that "… it is already clear that large-scale use of ethanol for fuel will almost certainly require cellulosic technology." Anderson and Fergusson (2006) went so far as to indicate that fuels derived from sugar or starch based biomass, often known as first generation biomass, should not be considered carbon neutral due to the fossil fuels used during production, transportation and processing. Greene and Roth (2006) concluded "… cellulosic ethanol simply delivers profoundly more renewable energy than corn ethanol."

These studies indicate that cellulosic ethanol can effectively give a good energy return on energy investment. Nevertheless, the design of processing plants and decisions regarding biomass production lands should minimize transport distance, and optimize plant operation to reduce energy costs.

4.2.4 Land Impacts

Another natural resource needed for the production of cellulosic ethanol is land. A substantial area of land mass will need to be dedicated to the growth of biomass to meet current energy policy goals (Perlack et al. 2005). Additionally, almost all environmental impact categories are affected by whether or not the land on which the biomass is grown is converted from forestland, agricultural land for a food crop, agricultural land for a non-food crop, agricultural use for ranchland, or marginal lands. The LCA for Bioenergy Sorghum (Section 3) assumed that the land used to grow the crop was converted from land that was already being used for crop growth and it was assumed that sustainable practices were used such that the land continued to have the ability to support life. Thus, there was no transformation.

When land is converted from one use to another, there is a potential for transformation. If land used to produce food crops is converted to produce energy crops, the price of food will increase, as discussed in Subsection 4.2.2. If land is converted from other crops, other industries will be affected and jobs could be lost in textile industries or elsewhere. If land is converted from forestlands, biodiversity and wildlife habitats can be affected (Tyner et al. 2010). This type of land conversion can also have economic effects. Flesher (2009) notes that using forestlands for biomass production does not give the best economic returns compared to lumber for building, and pulp for paper mills. If land is converted from marginal lands, some of the other environmental impact categories are increased as seen in this LCA and also in (Hertel et al.; Searchinger et al. 2008). This increase is due to the use of fertilizer, pesticides, and herbicides being applied to land where no chemicals were previously applied. This effect will be increased because marginal lands are likely to need significant input of nutrients and water to maintain productivity (Gopalakrishnan et al. 2009).

Increasing the amount of land used for agricultural purposes can cause significant change in “elemental fluxes to and from soil, erosion effects, and provision of ecosystem services” on those lands and surrounding lands as well (Miller 2009). To decrease the impact of this category, crops with the highest yield should be used. Also, the use of agricultural residues (e.g. wheat straw, corn stalks), mill residue (e.g. saw dust, wood scraps), urban wood waste (e.g. tree trimmings, construction debris), and forest residue (e.g. dead trees, culled trees) should be considered to lower the amount of biomass that must be grown.

4.2.5 Water Impacts

"Horse and carriage, love and marriage, water and energy are as intimately linked in all phases of their existence as any other couple (US Agency for International Development 2001)..." Energy and agriculture currently use the majority of water in the US. Surface water supplies have not increased in 20 years, and groundwater tables and supplies are dropping at a high rate (Sandia National Laboratories 2006). Thus, a significant increase in water usage from both these sources has the potential to critically affect water quantity.

The Committee on Water Implications of Biofuels Production in the United States of the National Research Council (2007) expressed concern that the irrigation demands associated with increased biomass production could promote unsustainable ground and surface water use that would degrade the aquatic ecosystem. Berndes (2002) projected that the US would draw more than 25% of the available water in order to produce the 1.3 billion tons of biomass per year the DOE has claimed is needed (Perlack et al. 2005). Gopalakrishnan (2009) concluded regarding water that- "If purpose-grown energy crops such as switchgrass or miscanthus are grown on productive agricultural land, the impact would be similar as direct utilization of food crops." Evans and Cohen (2009) conclude that "All feedstocks, when produced at the levels required to meet RFS (renewable fuel standards) volumetric production goals, will contribute substantially to water and land use challenges already facing the southeast." Ugarte et al. (2010) indicate that with proper crop management practices (no-till), and smart crop selection (high-yield drought resistant), production of the biomass necessary to meet US cellulosic ethanol goal will not necessarily place positive pressure on water demands.

The LCA process does not have a good method of addressing the impact of a process on water quantity. Nevertheless, water quantity is an important issue when considering a significant increase in agricultural production and it is an area of on-going research. To reduce the impact of this category, biomass feedstock that is drought resistant should be chosen so that no irrigation is required and a high yield can still be obtained in many areas of the US.

4.2.6 Climate Change Impacts

Climate change has been a primary driver for environmental research into alternative transportation fuel solutions. The IPCC was established by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) to assess scientific, technical and social-economic information relevant for the understanding of climate change. Their reports conclude that human activities are negatively impacting climate change through greenhouse gasses (Intergovernmental Panel on Climate Change 2007a; Intergovernmental Panel on Climate Change 2007b; Intergovernmental Panel on Climate Change 2007c). Data from NOAA and NASA indicate that the Earth’s average surface temperature has increased by between 1.2°F and 1.4°F since 1900 (Hansen et al. 2007; National Oceanic and Atmospheric Administration 2010). NASA also performed a study which found a 0.6°C rise in the earth’s average temperature over the last 30 year, which was attributed to an increase in greenhouse gases. The study asserted that even moderate additional increase could set in motion the disintegration of the West Antarctic ice sheet and Arctic sea ice (Hansen et al. 2007). Thirty three percent of the US energy related greenhouse gas emissions came from the transportation sector in 2008 (Energy Information Administration 2011), providing motivation to look into alternative fuels as a means to reduce greenhouse gas emissions and improve climate change factors.

It might seem that there would be greenhouse gas emissions savings when the ethanol is burned in a vehicle engine instead of the fossil fuels. The EPA reports emissions for petroleum at 2.4 kilogram CO_2 per liter and for ethanol at 1.6 kilogram CO_2 per liter (Environmental Protection Agency 2010). However, one liter of ethanol does not contain the same amount of energy; petroleum has 12.7 kilojoule per liter and ethanol has 7.9 kilojoule per liter. Thus, a car will burn more ethanol to go the same distance as a car burning petroleum gasoline; petroleum gasoline emits 0.42 kilograms CO_2 per kilojoule and ethanol emits 0.43 kilogram CO_2 per kilojoule. Given that these are very near the same, any greenhouse gas savings must come from the ethanol production. Some research indicates that due to nitrous oxide emissions during production of biomass, the CCP could be more affected by the production of corn ethanol (and some biodiesel) than the offsets from fossil fuel savings (Crutzen et al. 2008; Frondel and Peters 2007).

The Energy Information Administration (Energy Information Administration 2011) provides data that was used here to make some observations regarding climate change impact of cellulosic ethanol and the production of biomass in particular. The RFS became law in 2005 and since then US ethanol production has increased by 130%, and corn production has increased by almost 9% (2008 numbers). During this time period, the use of synthetic nitrogen fertilizer has increased by over 8%, and emissions from these fertilizers have increased by 10%.

Results of the LCA on the MixAlco process (Section 3) indicate that CCP for the production of cellulosic ethanol from Bioenergy Sorghum is sensitive to nitrogen emissions. To look at this example more specifically, consider that the LCA also found that production of enough high yield Bioenergy Sorghum for one MixAlco cellulosic ethanol plant produced 10.6 thousand tonnes CO_2 equivalents. If this number is scaled up to the RFS production requirement for the RFS in 2022 cellulosic ethanol goal, and all of the land used was land not previously used for agricultural purposes, then the CCP would be 3.7 million tonnes CO_2 equivalents. If it is further assumed that all of the fertilizer for this biomass production is new (consistent with the assumption regarding land use) then an additional 1.9 million tonnes CO_2 equivalents would result (St Clair et al. 2008). This CCP level is 0.08 percent of the greenhouse gas emissions produced in the US from all sources in 2008 (7053 million tonnes CO_2 equivalents). Thus, it seems possible that without careful consideration, the positive impacts on climate change intended by using cellulosic ethanol could be reduced by fertilizer production and use, an unintended consequence.

To reduce the impact to the CCP, continued analysis of the effects of nitrogen (and other greenhouse gases) are warranted, as well as optimization of land use and other crop management practices.

4.2.7 Other Chemicals and Emissions Impacts

4.2.7.1 Acidification

Acidification has negative impacts on natural resources and environment as well as man-made structures. When lakes and streams do not have sufficient buffering capacity to neutralize the acid, the water can become highly toxic to many species of animals. The "acid rain" that results from acidification also harms trees and other plants; it contributes to the corrosion of metals, and the deterioration of paint and stone.

In the LCA on Bioenergy Sorghum (Section 3), acidification was sensitive to nitrogen emissions. A significant increase in nitrogen fertilizer use as required by an increase in production of cellulosic biomass could have a large impact on the acidification. If the land was previously being used for crop growth, the increase in fertilizer use could be minimal because it is most likely that these chemicals were being used for the previous crop. If the land was converted from ranchland, forestland, or marginal land, the impact on acidification will be greater. To reduce the impact of the acidification potential category, crops should be selected that have less fertilizer requirements. Sustainable crop management practices which lower the need for fertilizer should be adopted.

4.2.7.2 Eutrophication

Eutrophication is an un-natural increase of nutrients in rivers, streams, lakes, and oceans, which leads to excessive plant growth (such as algae). When these plants die the dissolved oxygen in the water is reduced it causes other organisms to die. Thus, eutrophication impacts both water quality and biodiversity. Fertilizer run off into water sources is a known cause of eutrophication. Nutrient and sediment deposits into lakes and rivers were seen to increase in areas near where there has been increased agricultural feedstock production (Hill et al. 2006). Donner and Kucharik (Donner and Kucharik 2008; Donner et al. 2004) reported on the growth in the Gulf of Mexico hypoxic zone due to increased nitrogen deposits, which was attributed to the increased corn production driven by ethanol production (Donner et al. 2004).

The LCA on Bioenergy Sorghum (Section 3) indicated that eutrophication is primarily affected by phosphorus emissions. Similar to acidification, if the lands used for new biomass growth are converted from lands not previously growing crops, this category can be expected to see more impact. To reduce the impact of eutrophication, crop management practices which reduce the amount of fertilizer are needed.

4.2.7.3 Toxicity

Ecological and human toxicity were seen to be sensitive to pesticides/herbicides in the LCA on Bioenergy Sorghum (Section 3). The NRC concluded that current biofuel use has probably already negatively affected water quality and the projected future expansion stands to cause potentially significant harm (National Research Council 2007). Some of the pesticides and herbicides applied to crops leach through the soil with the water and percolate into the groundwater. Pesticides and herbicides also runoff into lakes and rivers. The effect of the runoff is amplified in areas near where there has been increased agricultural feedstock production (Hill et al. 2006; Pimentel et al. 2007). Pesticides can be a risk to wildlife, who are exposed to them when they eat plants or seeds with the residues. In some instances, wildlife may swallow pesticide granules directly. Pesticides and herbicides, however, are less likely to volatize (be converted to a gas) because they are tightly adsorbed to soil particles.

As discussed above, land that is converted from lands not previously growing crops will have a larger impact on toxicity. To reduce the impact of the toxicity potential impact categories, crops selection should consider the need for pesticides and herbicides, which varies for different crops. Kellogg et al. (2000) noted that “Corn leads all other crops-by a substantial margin-in total pesticide use.” Also, organic solutions or other sustainable crop management practices should be investigated.

4.3 Stakeholders and Decision Makers

Although there is general agreement in the US that energy independence is important, there are significant differences of opinion among stakeholders and decision makers as to which approaches should be taken to achieve energy independence. Also, consensus has not been reached regarding the importance of the environment in relation to that of energy security. It will be difficult (impossible) for a comprehensive energy policy to address the concerns of all interested parties. This subsection will discuss these parties in turn, and what they support and oppose with regards to cellulosic ethanol and its place in energy policy.

4.3.1 Obama Administration

The current US administration has been consistently supportive of alternative energy, and energy independence has been set as a priority (Whitehouse 2010). President Barak Obama campaigned on this issue, indicating that the nation must "… face one of the greatest challenges of our time: confronting our dependence on foreign oil, addressing the moral, economic and environmental challenge of global climate change, and building a clean energy future that benefits all Americans (Obama and Biden 2008)." The New Energy for America plan put forward at the time included several components that were designed to support alternative transportation energy including cellulosic ethanol, efforts to increase the number of Plug-In Hybrids, and a cap-and-trade program to reduce greenhouse gas emissions (Obama and Biden 2008).

This support was continued once Obama took office with changes to the National Renewable Fuel Standards that proposed a shift away from corn ethanol to higher-yield cellulosic ethanol, and later by significant investments in the development of renewable energy and clean technologies in the Recovery Act. The Office of Science and

Technology Policy (OSTP), which advises the president, produced a report with recommendations to accelerate the pace of change in energy technologies, with a strong emphasis on “green” technologies (President's Council of Advisors on Science and Technology 2010). The Council of Economic Advisors advised jump starting the “clean energy economy” through $60 billion in direct spending and $30 billion in tax credits from the American Reinvestment and Recovery Act of 2009 (Council of Economic Advisors 2010).

President Obama has generally sought to limit new drilling efforts in the US to “balance the need to produce more domestic energy while protecting natural resources (Broder 2010).” However, in early April 2010, Obama proposed to allow drilling of parts of the Atlantic and Alaska coastlines. This decision was largely seen as a political move to appease Republicans, who for the most part approve of increasing domestic sources of oil through new and offshore drilling. The BP oil spill occurred later in April 2010 resulting in increased efforts by the environmental lobby groups (Oceana, National Wildlife Federation, Greenpeace, etc.) to prevent continued offshore drilling (Chebium 2010). A temporary ban was indeed put in place and in December 2010, Obama reversed his April 2010 decision regarding new drilling, siting too much environmental risk.

The Administration’s FY 2011 budget request also provides some insight into energy policy strategy. The request would increase funding for climate change research in the US Global Change Research Program, the National Oceanic and Atmospheric Administration, NASA, DOE, the Department of the Interior (DOI), and the NSF. In addition, the DOE budget request places a priority on investing in innovative solutions to energy challenges and providing clean, secure energy (Intersociety Working Group 2010).

4.3.2 United States Congress

Members of Congress have the ability to create new and revise current legislation, and thus they are important in the policy making process. The current Congress has a democratic majority in the Senate and a republican majority in the House of Representatives. The topic of energy is generally considered important by members. Republicans have traditionally supported policy that addresses energy security as the priority for addressing the US's continued reliance on fossil fuels. These members tend to focus on the need to move from reliance on *foreign* oil. This focus is seen in support of efforts to retrieve domestic oil from more difficult locations and through more intensive processes. This includes activities such as offshore drilling, and drilling in locations that are of environmental concern to some.

Democratic members have generally supported policy that addresses energy security but with a simultaneous significant weight placed on environmental considerations. These members tend to oppose efforts to increase domestic fossil fuel supplies, and support the development of alternative fuels. The non-renewable nature of fossil fuels, anthropogenic climate change, and the potential damage caused by drilling (such as seen in the BP spill) are the motivating environmental concerns.

Congressional decision making is also influenced by their desire to benefit their constituency (Kingdon 2003). This fact brings politics into the policy making decision process, in that a member will support a policy that benefits his constituents even across party lines. Policy makers in agricultural states will tend to support biofuels, and those in gulf states tend to support offshore drilling, and so on. For example, fifteen senators from both parties signed a letter in November 2010 supporting the extension of US ethanol subsidies. The letter was led by republican senator from Iowa, Chuck Grassley, and democratic senator from North Dakota, Kent Conrad with bipartisan signatories mostly from the farm belt states. A rebuttal letter was then created by a democratic senator from California, Diane Feinstein, and a republican senator from Arizona, Jon Kyl, stating their opposition to the continuation of the ethanol subsidies. This rebuttal letter was signed by a bipartisan group of 17 senators from 11 states (none in the farm belt).

Members of Congress can also influence policies through the activities of powerful committees and caucuses. The US House of Representatives Committee on Science, Space and Technology, currently chaired by a Republican, Ralph Hall from Texas, has an Energy and Environment Subcommittee. In June 2010, this subcommittee saw testimony regarding the safety of underwater drilling technology and questioned the need for a moratorium on deepwater drilling (Committee on Science Space and Technology 2010). Also in June 2010, they heard testimony regarding the economic and reliability challenges of alternative energy. Representative Randy Neugebauer, a Republican Member from Texas, indicates that "Despite many years—even decades—of growth in subsidies and vast resources targeted towards research and development, renewable energy sources remain significantly more expensive than conventional counterparts." He does go on to note that the subsidies, along with Renewable Portfolio Standard mandates have led to progress in the integration of renewable energy onto the electric grid. In November 2010, this subcommittee saw testimony on the uncertainty in climate science and long term climate models (Committee on Science Space and Technology 2010).

The US Senate Committee on Energy and Natural Resource is currently chaired by Jeff Bingaman, a democrat from New Mexico (Committee on Energy and Natural Resources 2011). In September 2010, the Subcommittee on Energy received testimony on the effectiveness of the DOE's Loan Guarantee Program for encouraging the near-term deployment of clean energy technology. Also, in September 2010, testimony was heard examining the role of strategic minerals in clean energy technologies.

There is also a Congressional Biofuels Caucus that supports efforts to grow the US ethanol industry. This caucus includes 30 members from the House of Representatives, with 19 democratic members and 11 republican. The House members are from 17 different states (California, Illinois, Indiana, Iowa, Kansas, Massachusetts, Michigan, Minnesota, Missouri, Montana, Nebraska, New York, North Carolina, North Dakota, Ohio, South Dakota, Virginia). There are 11 members from the Senate, with 8 democratic members and 3 republican. The Senate members are from 9 different states (Indiana, Missouri, Kentucky, North Dakota, Illinois, Iowa, Arkansas, Nebraska, South Dakota).

Finally, congressional staff also interface regularly with experts and interest groups to get ideas and hone policy proposals. The congressional staff that serve on entities such as Congressional Budget Office (CBO), Congressional Research Service (CRS), and the Government Accountability Office (GAO) usually have significant experience and expertise and can generate support for particular policies among congressmen. In 2010, the CBO evaluated the cap and trade program and biofuels tax credit ideas. They also looked at climate change programs and how reducing emissions could affect employment (Congressional Budget Office 2010). In 2010, CRS provided a comparison of four energy and climate change legislative proposals. They also evaluated energy tax policy, the biomass crop assistance program, and energy and water resource development (Congressional Research Services 2011). The GAO also studied the cap and trade program and the DOE's Loan Guarantee Program in 2010.

4.3.3 State Entities

"The desire to reduce US dependence on foreign fuel and to promote economic development at home for rural areas has contributed to the rapid growth in US biofuel production (Keve et al. 2010)." Twenty five states introduced some form of biofuels legislation in 2009. In several states multiple bills were introduced. This legislation was aimed at increasing biofuels technology development, production, distribution and use through incentives such as tax credits and rebates, and grants and loans. Thirty eight states currently have these types of state policies (Table 18).

Agricultural states will often work together in support of biofuels and tend to be more aggressive in their legislative efforts toward this end. However, even Big Oil states see some economic potential in the production of biofuel and many of them also have biofuels legislation (Table 18).

4.3.4 Industry

There are several different stakeholders who have a significant interest in the success (or failure) of alternative energy in general and cellulosic ethanol in particular. The most prominent of these is business and industry. In the case of transportation energy policy, there is a long list of keenly interested businesses. These companies include but are not limited to: energy companies (Chevron, Exxon, Shell, BP, etc.), drilling companies (Schlumberger, Transocean, etc.), automobile production companies (Ford, Chevrolet, General Motors, Honda, Toyota, etc.), companies that rely on primarily on trucks for transporting goods (Walmart, grocery stores, etc.), agricultural companies (Monsanto, Archer Daniels Midland, etc.), and last but not least, alternative energy companies (POET LLC, Growth Energy, etc.).

While traditional oil companies definitely continue to support the production of domestic oil, most of them are in the process of transforming themselves into energy companies and embracing alternative fuels to varying degrees. For example, Chevron is investing millions of dollars in biofuels technologies (Chevron 2011). Policies requiring the use of biofuels become an economic incentive for traditional oil companies. In addition these energy companies are beginning to partner with biofuels development companies as discussed in Subsection 4.2.1. It also should be noted that most of these companies are international and so the push for domestic production of transportation fuels (oil or alternatives) may sometimes conflict with their business plans.

Car companies generally support the production and use of domestic oil. Some of these companies have also begun to invest in ethanol technologies as discussed in Subsection 4.2.1. However, because their infrastructure and designs are primarily set up for the use of fossil fuels, incentives and regulations have been required to motivate these companies to move toward alternative fuels in the design of their cars.

Agricultural and alternative fuel production companies are obvious supporters of biofuels in general. However, incentives are required to transition from corn ethanol to cellulosic ethanol, and move to commercial scale.

4.3.5 Interest Groups

In addition to industry, there are many different groups of people with significant interest in the issue of energy in the US. These stakeholders have a variety of reasons for their interest including money, power, and social, ethical, and environmental concerns. Interest groups are able to have a noticeable impact on policy through activities such as sending delegations to visit key Congress members, writing letters to Congress and the Administration, and making use of media outlets to send messages.

Environmental groups have been long time opponents of fossil fuels but are also concerned about the potential environmental implications of some biofuels. Consumer advocates are concerned about rising prices of consumer products, especially products such as food. Other interest groups are concerned about the financial stability of their industry (oil, corn ethanol, other biofuels, cars, drilling, etc.).

Agricultural interest groups that are active in policy making for biofuels will sometimes partner in their lobbying activities. For example, the National Corn Growers Association and the Iowa Renewable Fuels Association are lobbying for the continuation of corn ethanol (only/mostly). However, sometimes they will team with other renewable fuels organizations to support all biofuels (corn ethanol, cellulosic ethanol, biodiesel). Many food and feed production organizations (e.g. Grocery Manufactures Association, American Meat Institute, National Chicken Council) do not support corn ethanol because it raises the price of corn, but may support other types of biofuels.

Other ideological advocacy groups also oppose corn ethanol. For example an unlikely group of organizations recently teamed to oppose the continuation of federal corn ethanol subsidies including: Moveon.org (an anti-war activist group), FreedomWorks (a Tea Party activist group), Public Citizen (a consumer advocacy group), Sierra Club (an environmental activist group), American Bankers Association (organization representing bankers), National Taxpayers Union (group that advocates tax reductions), and Competitive Enterprise Institute (libertarian group) (Beckel 2011).

4.4 Policy Recommendations- Cellulosic Ethanol Enhancement Act

A new policy, The Cellulosic Ethanol Enhancement Act (CEEA), will be outlined in this subsection based on the information gleaned from both the environmental and the policy evaluation. This act will include both current and new policy elements, which will be discussed here with regards to their ability to increase the environmentally responsible production and use of cellulosic ethanol. Groups which might support or oppose various policy components will also be discussed.

The recommended policy components of the CEEA resulted from balancing the varied goals, concerns, and issues. In the end the process was an optimization where goals were prioritized, desires were considered, and issues were minimized. The primary goal was the successful creation of a sustainable cellulosic ethanol market. The driving force for this goal came primarily from two motivations: 1) energy independence, seen here as the reduction of imported transportation fuels, and 2) reduction of the deleterious effects of greenhouse gasses. Both these motivations were considered in each policy component. It was also considered desirable to help grow the economy and workforce, and to advance technologies in general. Minimizing the environmental impact on large and small scales was seen as important, as well as the any negative social, cultural, and/or economic impacts.

The analyses performed in this dissertation indicated that a biofuel created from cellulosic biomass has several advantages over current transportation fuels, including corn ethanol, when considering the goals and motivations outlined. Thus, the recommended policy components will be applied to cellulosic ethanol in particular. That is not to say that these components might not also be for other types of biofuels. The objective is to ensure that cellulosic ethanol specifically, but not necessarily uniquely, benefits from the policies. The components of the new act will first be described in detail. Following that will be a summary of the act as a whole.

4.4.1 Existing Policy Components

This subsection will discuss the component of the CEEA which have roots in existing policy components. Modifications have been made to provide focus on and benefit to cellulosic ethanol as appropriate and these changes will be noted.

4.4.1.1 Renewable Fuel Standards

Renewable Fuels Standards are currently in place that set a mandatory blend level for renewable fuels and establish a greenhouse gas reduction criterion. Several states also have their own RFS to encourage biofuels production in their state.

The biofuels industry is a strong supporter of these requirements because they create demand for their product. The oil industry generally opposes them for the same reason. The environmental lobby is conflicted due to concerns about the food verses fuel debate with corn (and other feed grains) ethanol. However, this policy is designed to encourage the production and use of more advanced biofuels technologies over time.

Cellulosic ethanol production benefits from this policy, which creates demand for ethanol in general and cellulosic ethanol in particular. The most benefit is gained by the RFS being set such that the oil companies are strongly encouraged to support alternative fuel production. This standard also encourages the growth of corn ethanol industry to some degree. *The RFS is recommended as a crucial part of the CEEA because it specifically creates a market for cellulosic ethanol, which increases over* *time. This requirement provides leverage for other policy components which rely on the creation of demand for the product.*

4.4.1.2 CAFE Standards

The CAFE standards are currently in the energy policy portfolio but only for light duty vehicles. The EPA and DOT are proposing to apply CAFE standards to medium to heavy duty vehicles and to extend the timeline for the standards through 2025. These standards were established to reduce the fuel consumption in the US, and consequently reduce petroleum use (and import) and greenhouse gas emissions. The standards also serve as an incentive for automakers to design and build more fuel efficient vehicles. The automobile industry opposes increases in the standards. The environmental lobby supports these standards. While this policy will still benefit corn ethanol, it will also encourage the growth of advanced biofuels including cellulosic ethanol.

This standard is primarily environmental legislation. However, it does directly encourage the use of biofuels in general, because credits are given for the use of E85. *CAFE standards for light, medium, and heavy duty vehicles are recommended as part of CEEA. A change to the existing policy is suggested such that credit be given for the use of cellulosic ethanol in particular.*

4.4.1.3 Clean Air Act Requirements

Clean Air Act requirements are currently in place to use RFG made by mixing gasoline with an oxygenate (such as ethanol). These standards are designed to reduce air pollutants including greenhouse gases. The oil industry generally opposes these standards because it reduces the amount of petroleum used and requires them to invest in oxygenate fuels. The environmental lobby is in favor of these regulations because of the benefits to air quality, which is primarily a reduction in acid rain. The biofuels industry is in favor of these standards because they create demand for their product.

Cellulosic ethanol is an oxygenate which can benefit from this policy. This policy also increases demand for corn ethanol, especially now that there is no large scale production of cellulosic ethanol. *Clean air act requirements are recommended as part of CEEA. A change is suggested to existing policy such that a credit be given for the use of cellulosic ethanol in particular.*

4.4.1.4 Grants for Production of Advanced Biofuels

The goal of this policy is to spur innovation and investment in the production of advanced biofuels through grants to produce advanced biofuels. If the RFS are to be met, many additional cellulosic ethanol plants are needed. Some of these grants are currently used for research and development, and some are for commercialization and deployment. In general the environmental lobby is in favor of support for biofuels, except for corn ethanol which is viewed as using too much natural resources. The biofuels industry and agricultural lobby and industry are in favor. Several states also have these types of grants to encourage biofuels production in their state. Some of these state level grants are specific to the type of biofuel generally produced in that state.

These grants are recommended as part of the CEEA. A change to the policy is suggested such that grants for both research and development, and commercialization and deployment be awarded for cellulosic ethanol in particular. There are several different cellulosic ethanol production processes and this type of grant could incentivize investment in these technologies. Because these grants are designed to be focused on new biofuels technologies, they should not be used on corn ethanol production.

4.4.1.5 Grants for the Biofuels Production and Distribution Infrastructure

This policy is currently in place for E-85. The goal of this policy is to offset the cost of changing infrastructure from a fossil fuel based system. This expense is seen as a significant barrier to the success of biofuels. The biofuels and agricultural industry, and environmental lobby support this policy in general. Many believe it would be best to structure the grants such that all biofuels can benefit. Several states offer these grants to help biofuels producers. *These grants are recommended as part of the CEEA. A change is suggested to award grants that assist the creation of infrastructure for the production of cellulosic ethanol in particular.*

4.4.1.6 Grants for Bioenergy Crop Producers

The goal of this policy is to encourage the development of crops specifically designed for use as biofuel feedstock. Currently these grants are given for research and development, and also for deployment. Also, some grants are currently specified to be used for biodiesel and the use of sugar in the production of biofuels. The biofuels and agricultural industry and the environmental lobby support this policy. It is unlikely that this policy would encourage corn ethanol because corn is a well-established crop.

As seen in the LCA in Section 3, it is assumed that crops developed for the purpose of being biofuels feedstocks will not be irrigated. Therefore, research into making high yield crops that use little water will be important to conserving water and land as natural resources, when considering the large volume of feedstock necessary to meet the RFS.

The LCA research also indicated that the potential positive climate change benefits of using biofuels are dependent on the amount of nitrogen applied as fertilizer. In addition, several pesticides were seen to be potential problems for human and ecological toxicity. When the production of cellulosic ethanol is scaled up to the RFS, these effects will be magnified. Research into organic and other practices should be encouraged.

These grants for bioenergy crop research and development are recommended as part of the CEEA. A suggested change is ensure that they are used to encourage research in areas of concerns. Important examples include research regarding agricultural practices to reduce the amount of land, water, fertilizer, and pesticides/herbicides used. In addition, it is suggested that these grants be awarded for cellulosic ethanol in particular.

4.4.1.7 Loan Guarantees for Commercial Scale Bio-Refineries

This policy provides loan guarantees for development and/or retrofitting of commercial scale bio-refineries with the goal of moving the biofuels industry toward large scale commercial production. It is supported by biofuels and agriculture industry as long as it applies to all biofuels. The policy is supported by the environmental lobby. Several states offer these types of loans as well, though they may be specific to a certain type of biofuel. There are also low interest loans offered by some states for biofuels producers. This technology should not benefit corn ethanol as corn ethanol is already at commercial scale.

This policy is recommended as part of CEEA because it incentivizes moving the technology to a commercial scale. A change is recommended that it specifically call out cellulosic ethanol, especially because the technology development of cellulosic ethanol appears to be economically stalled at this developmental stage.

4.4.2 New Policy Components

4.4.2.1 Federal Study Natural Resource Depletion from Biofuels

Grants such as these are not currently part of the policy portfolio. However, the results of the LCA indicated that increasing biomass production could cause depletion of our natural resources, primarily land and water. If the land used for growth of cellulosic biomass is land that was previously used for agricultural purposes, it is likely replacing a food or feed crop. This situation causes ethical concerns as discussed previously. If the land used for biomass growth is converted from marginal lands, there will be more environmental impact because the land was previously being used for crops, it is likely that at least some fertilizers and pesticides/herbicides were being used. However, if the land was not being used for crop growth, then it is possible that no chemicals were being used on that land and there will be a large increase in the use of these chemicals resulting from growing crops on this land. In addition, it is likely that more fertilizers and water will be necessary because the lands were already determined to be marginal (i.e. possibly not good for agricultural use).

It is recommended as part of the CEEA that a study be performed specifically on this topic to find a sustainable solution including optimal combinations of land use to minimize the impact on both the environment and the food and fee supply and cost. This solution could include some use of marginal lands, and optimization of necessary crop rotations to use lands that are already used for crop growth.

It seems certain that an increase in biomass crop development will result in an impact on water resources. Even if most of these crops are not irrigated, they will use water that could have/would have been used elsewhere and this fact will affect the watershed. *Thus, it is also recommended as a part of the CEEA that a study be* *performed to look at potential impacts of large scale biomass production on water resources and make suggestion to provide a sustainable solution which minimizes the impact.*

These studies can be the responsibility of the Congressional Research Service (CRS) and annual reports should be delivered to Congress on the findings.

4.4.2.2 Land and Water Use Impact Statement

No restrictions on land or water use are currently used as part of the energy policy portfolio. The National Environmental Policy Act (NEPA) requires an Environmental Impact Statement for actions that significantly affect the quality of the human environment. *Because of the potential impact on land and water as discussed above, it is recommended that the CEEA include a Land and Water Use Impact Statement requirement for cellulosic ethanol producers to ensure careful consideration of these impacts before production begins.*

4.4.2.3 Fertilizer, Pesticide and Herbicide Use Database

There is currently no comprehensive database available to the public and researchers on the amounts and locations of fertilizer, pesticides and herbicides that are applied to crops in the US. If biomass production is significantly increased, it will be necessary and useful to have detailed data regarding which chemicals are being applied, where, and at what quantities. *It is recommended as part of the CEEA that a detailed database of fertilizer, pesticide and herbicide use in the US be assembled, maintained, and made readily available to the public by the USDA, and the EPA.*

4.4.3 Summary of Cellulosic Ethanol Enhancement Act

In summary, proposed here is an act designed to enhance the sustainable environmentally responsible development of cellulosic ethanol. This act includes:

1) the RFS, which creates demand for cellulosic ethanol by specifically calling for an increase in the amount used for transportation fuel;
2) a continuation of the CAFE standards for small, medium, and heavy vehicles with a credit specifically given for use of cellulosic ethanol;
3) a continuation of the Clean Air Act Requirements with a credit given specifically for the use of cellulosic ethanol;
4) grants to support the research, development, deployment, and commercialization of cellulosic ethanol including the biomass, the biofuels process, and infrastructure;
5) loan guarantees for the commercialization of cellulosic ethanol in particular to help the biofuel move to the next level of production;
6) studies of natural resource depletion impacts due to the large-scale production of cellulosic ethanol, designed to provide methods for mitigating negative impacts to land, water and other natural resources;
7) regulations requiring land and water use impact statements and;
8) the creation of a fertilizer, pesticide and herbicide database associated with the production of cellulosic ethanol to help manage potential environmental consequences.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Motivating Factors

With ever increasing energy demands to fuel our technologically advanced society, the fact that the US produced 11% of the world's petroleum and consumed 22% in 2009 (Energy Information Administration 2011) has become a significant concern for many. This concern has been a motivation to increase US energy independence and security by reducing the amount of imported oil. Additionally, in 2010 the US produced 19% of the world's energy related greenhouse gas emissions (Energy Information Administration 2011). The only country that produced more emissions was China (23%). Thus, the potential impacts on climate change caused by carbon dioxide emissions from the burning of fossil fuels has also been a motivating factor to find alternative fuel sources. For both of these motivations, many have looked to biofuels as a potential partial solution.

The first large scale foray into biofuels for the US was ethanol, primarily derived from corn. There has been much debate about the wisdom of the selection of corn as a feedstock, which has been discussed in this dissertation. Corn has a high sugar content, which can be desirable in a feedstock, and is a crop grown in many states in the US with an established infrastructure for production. However, the energy return on energy invested has not been overwhelming, and the social and ethical concerns regarding the use of food and feed crops for fuel remain. Thus, cellulosic ethanol is considered a promising alternative that offers the possibility of reducing the amount of fossil fuels imported, while simultaneously reducing potential impacts on climate change. The energy return on energy invested is higher than for corn, and there are plenty of crops to choose from which are not food or feed crops. Given the possibilities, researchers are now beginning to further explore the environmental impacts of cellulosic ethanol.

5.2 Dissertation Research Conclusions and Recommendations

This dissertation research performed an environmental evaluation using the Life Cycle Assessment technique on Bioenergy Sorghum, a crop which was specifically produced as an energy crop, used in a conversion process (MixAlco version 1) that can produce cellulosic ethanol. Results indicated that the conversion process is highly optimized with minimal environmental concerns. Analysis of the crop production however demonstrated that there are a few areas which will benefit from further investigation.

Firstly, if the large scale production of crops is to be sustainable, the depletion of natural resources, especially land and water, will need to be mitigated. Further, decisions regarding how land is converted or transformed accentuates other potential environmental impacts as well, and needs to be optimized. Secondly, fertilizer production and application will lead to increased emissions that could reduce the positive climate change impacts which originally provided motivation to use the biofuel. Thirdly, pesticides and herbicides often used for successful crop production will increase emissions, run off, leaching, and volatilization. The full impact of the large scale introduction of these chemicals, both fertilizers and pesticides/herbicides, needs to be examined in detail on global and local scales and databases created and made widely and easily available to researchers.

This dissertation research further evaluated current energy policy and proposed a new act, the Cellulosic Ethanol Enhancement Act, to encourage the sustainable environmentally responsible success of cellulosic ethanol in the US. This act included a specification of existing elements of policy as well as new policy components. The act used:

- existing regulations to create significant demand for cellulosic ethanol;
- standards and credits to further encourage its use;
- grants and loan guarantees to support research, development, deployment, and commercialization;
- studies and regulations to mitigate potential negative environmental impacts.

5.3 Future Research Recommendations

Several areas which could benefit from further research were identified. During the Life Cycle Inventory Analysis (input and output data gathering) phase of the LCA, some gaps in data availability were noted. Information on the amounts of chemicals applied to different crops associated with specific locations (by counties for instance) is needed for environmental analyses. A database of this information needs to be created and made readily available for researchers.

A standard method for dealing with fate and regional differences in LCA methodology should be developed for the impact categories where this could be important including toxicity categories and acidification and eutrophication. During the Impact Assessment phase of the LCA, it was noted that there were no readily available and generally accepted characterization factors for the US in any impact category. Having this type of data could increase the accuracy of the results and allow for useful comparisons and conclusions. The environmental research to gather this data should be performed in such a way to be accepted by SETAC and other international organizations involved in LCA.

Research into a quantitative method to deal with land use that is consistent with LCA methodology is an active area of research, which should be continued. Because land can be used in so many different ways with regards to environmental impact, this category may need to be further subdivided. A focus on transformation of and to agricultural uses, in particular would benefit biofuels research. Given sustainability issues associated with large scale crop production, further research into a method for accounting for the loss of life support functions is needed.

In general, water is currently treated as a renewable resource, which does not allow for an accounting of the potential impact of large scale use of water. The impact of water shortages due to groundwater extraction leading to lower water tables, introduction of water from other areas and consequent changes needs to be investigated. The latest methodologies for water resource and watershed management should be applied to LCA.

There have also been some attempts at using a more rigorous approach in LCA to the evaluation of energy as a resource. The use of the Abiotic Depletion Potential could be improved by either making a separate category or subdividing it into depletion of energy and depletion of other minerals. This separation seems necessary due to the differences in the type of available data. Research into methods such as the use of thermodynamics and exergy in the case of petroleum and other fossil fuels should also be further investigated for use in LCA.

It would be useful to perform a LCA, similar to the one performed here, with other potential energy crops, such as switch grass, or miscanthus, in such a way that the analyses could be directly compared. It would also be useful to perform this same analysis of the MixAlco process, for the version that is used at the commercial scale. In this way, it can be determined if the optimal conditions seen in this analysis are able to be maintained at the larger scale.

If the data were made available, it would be useful to do a LCA of another biofuels process in such a way that it could be directly compared to the analysis done here. This analysis would help demonstrate whether or not it is a good assumption that the conversion process is not generally environmentally impactful.

Finally, it would be useful to perform a policy evaluation of cellulosic ethanol used in conjunction with a hybrid vehicle to encourage further energy savings.

REFERENCES

Aden, A., Ruth M., Ibsen K., Jechura J., Neeves K., Sheehan J., and B., W. (2002). "Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover." *NREL/TP-510-32438*, National Renewable Energy Laboratory, Golden.

Akiyama, H., Yan, X. Y., and Yagi, K. (2010). "Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N2O and NO emissions from agricultural soils: meta-analysis." *Global Change Biology*, 16(6), 1837-1846.

Alexander, A. G. (1985). *The energy cane alternative*, Elsevier Sciences Limited, Amsterdam, Netherlands.

Amphlett, J. C., Mann, R. F., Peppley, B. A., Roberge, P. R., Rodrigues, A., and Salvador, J. P. (1998). "Simulation of a 250 kW diesel fuel processor/PEM fuel cell system." *Journal of Power Sources*, 71(1-2), 179-184.

Anderson, G. Q. A., and Fergusson, M. J. (2006). "Energy from biomass in the UK: Sources, processes and biodiversity implications." *Ibis*, 148, 180-183.

Balat, M., and Balat, H. (2009). "Recent trends in global production and utilization of bio-ethanol fuel." *Applied Energy*, 86(11), 2273-2282.

Barbanti, L., Grandi, S., Vecchi, A., and Venturi, G. (2006). "Sweet and fibre sorghum (Sorghum bicolor (L.) Moench), energy crops in the frame of environmental protection from excessive nitrogen loads." *European Journal of Agronomy*, 25(1), 30-39.

Beckel, M. (2011). "Senators supporting ethanol subsidies reap riches from corn interests." Open Secrets Blog, http://www.commondreams.org/headline/2011/01/03-4. January 20, 2011.

Berndes, G. (2002). "Bioenergy and water: The implications of large-scale bioenergy production for water use and supply." *Global Environmental Change-Human and Policy Dimensions*, 12(4), 253-271.

Blanco, S. (2010). "Oil giant total invests in cellulosic ethanol company Coskata's latest funding round." *Autobloggreen*. http://green.autoblog.com/2010/04/28/oil-giant-total-invests-in-cellulosic-ethanol-company-coskatas/. January 11, 2011.

Bouwman, A. F. (1996). "Direct emission of nitrous oxide from agricultural soils." *Nutrient Cycling in Agroecosystems*, 46(1), 53-70.

Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H. (2002a). "Emissions of N2O and NO from fertilized fields: Summary of available measurement data." *Global Biogeochemical Cycles*, 16(4), 6.1-6.13.

Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H. (2002b). "Modeling global annual N2O and NO emissions from fertilized fields." *Global Biogeochemical Cycles*, 16(4), 28.1-28.8.

Brentrup, F., Kusters, J., Kuhlmann, H., and Lammel, J. (2001). "Application of the life cycle assessment methodology to agricultural production: An example of sugar beet production with different forms of nitrogen fertilisers." *European Journal of Agronomy*, 14(3), 221-233.

Brentrup, F., Kusters, J., Kuhlmann, H., and Lammel, J. (2004). "Environmental impact assessment of agricultural production systems using the life cycle assessment methodology: I. Theoretical concept of a LCA method tailored to crop production." *European Journal of Agronomy*, 20(3), 247-264.

Broder, J. M. (2010). "Obama oil drilling plan draws critics." *New York Times.com*, http://www.nytimes.com/2010/04/01/science/earth/01energy.html?_r=1& pagewanted=2. March 31, 2010.

Caserta, G., Bartolelli, V., and Mutinati, G. (1995). "Herbaceous energy crops: A general survey and a microeconomic analysis." *Biomass & Bioenergy*, 9(1-5), 45-52.

Charles, M. B., Ryan, R., Ryan, N., and Oloruntoba, R. (2007). "Public policy and biofuels: The way forward?" *Energy Policy*, 35(11), 5737-5746.

Chebium, R. (2010). "Obama: No drilling for oil off N.J. coast." Courier Post Washington Bureau. http://www.courierpostonline.com/article/20101202/ NEWS01/12020321/Obama-No-drilling-for-oil-off-N-J-coast. December 2, 2010.

Chevron. (2011). "Emerging Energy." http://www.chevron.com/globalissues/ emergingenergy/. January 26, 2011.

Chirinda, N., Carter, M. S., Albert, K. R., Ambus, P., Olesen, J. E., Porter, J. R., and Petersen, S. O. (2010). "Emissions of nitrous oxide from arable organic and conventional cropping systems on two soil types." *Agriculture Ecosystems & Environment*, 136(3-4), 199-208.

Cleveland, C. J. (2001). "Net energy from the extraction of oil and gas in the United States." *Energy*, 30(5), 769-782.

Cleveland, C. J. (2005). "Net energy from the extraction of oil and gas in the United States." *Energy*, 30(5), 769-782.

Committee on Energy and Natural Resources. (2011). "Hearing list." US Senate. http://energy.senate.gov/public/index.cfm?FuseAction=Hearings.ByMonth. January 25, 2011.

Committee on Science Space and Technology. (2010). "Hearings and markups." US House of Representatives. http://sciencedems.house.gov/publications/hearings_markups.aspx. January 25, 2011.

Congressional Budget Office. (2010). "Climate Change." Economic and Budget Issue Brief, http://www.cbo.gov/publications/collections/collections.cfm?collect=9. January 26, 2011.

Congressional Research Services. (2011). "Resources, Science, and Industry." http://www.loc.gov/crsinfo/research/rsrch-resources.html. January 26, 2011.

Council of Economic Advisors. (2010). *Economic Report of the President*, The United States Government Printing Office, Washington D.C.

Couture, T., and Cory, K. (2009). "State Clean Energy Policies Analysis (SCEPA) project: An analysis of renewable energy feed-in tariffs in the United States." *NREL/TP-6A2-45551*, National Renewable Energy Laboratory, Golden.

Crutzen, P. J., Mosier, A. R., Smith, K. A., and Winiwarter, W. (2008). "N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels." *Atmospheric Chemistry and Physics*, 8(2), 389-395.

Dalgaard, R., Halberg, N., Kristensen, I. S., and Larsen, I. (2006). "Modelling representative and coherent Danish farm types based on farm accountancy data for use in environmental assessments." *Agriculture Ecosystems & Environment*, 117(4), 223-237.

Derwent, R. G., Jenkin, M. E., and Saunders, S. M. (1996). "Photochemical ozone creation potentials for a large number of reactive hydrocarbons under European conditions." *Atmospheric Environment*, 30(2), 181-199.

Derwent, R. G., Jenkin, M. E., Saunders, S. M., and Pilling, M. J. (1998). "Photochemical ozone creation potentials for organic compounds in northwest Europe calculated with a master chemical mechanism." *Atmospheric Environment*, 32(14-15), 2429-2441.

Donner, S. D., and Kucharik, C. J. (2008). "Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River." *Proceedings of the National Academy of Sciences of the United States of America*, 105(11), 4513-4518.

Donner, S. D., Kucharik, C. J., and Foley, J. A. (2004). "Impact of changing land use practices on nitrate export by the Mississippi River." *Global Biogeochemical Cycles*, 18(1), GB1028.1-GB1028.21.

Elander, R. T., Dale, B. E., Holtzapple, M., Ladisch, M. R., Lee, Y. Y., Mitchinson, C., Saddler, J. N., and Wyman, C. E. (2009). "Summary of findings from the

Biomass Refining Consortium for Applied Fundamentals and Innovation (CAFI): Corn stover pretreatment." *Cellulose*, 16(4), 649-659.

Elert, G. (2009). "The Physics Hypertextbook." http://physics.info/energy-chemical/. November 19, 2010.

Energy Independence and Security Act. (2007). First Session of 110th Congress. Sections 202-244. January 4, 2007.

Energy Information Administration. (2011). "Annual Energy Outlook 2011 Prerelease." *DOE/EIA-0383ER(2011)*, US Department of Energy, Office of Integrated Analysis and Forecasting, Washington D.C.

Environmental Protection Agency. (2010). "Regulation of Fuels and Fuel Additives: 2011 Renewable Fuel Standards." *EPA–HQ–OAR–2010–0133*, Environmental Protection Agency, Washington D.C.

Evans, J., and Cohen, M. (2009). "Regional water resource implications of bioethanol production in the Southeastern United States." *Global Change Biology*, 15(9), 2261-2273.

Farrell, A. E., Plevin, R. J., Turner, B. T., Jones, A. D., O'Hare, M., and Kammen, D. M. (2006). "Ethanol can contribute to energy and environmental goals." *Science*, 311(5760), 506-508.

Flesher, J. (2009). "Bio-fuel growth raises concerns about forests." The Washington Post.com, http://www.washingtonpost.com/wp-dyn/content/article/2009/11/23/AR2009112300472_pf.html. November 23, 2009.

Food Conservation and Energy Act. (2008). 2nd Session of 110th Congress. Sections 9003-9012.

Fowler, D., Cape, J. N., Coyle, M., Smith, R. I., Hjellbrekke, A. G., Simpson, D., Derwent, R. G., and Johnson, C. E. (1999). "Modelling photochemical oxidant formation, transport, deposition and exposure of terrestrial ecosystems." *Environmental Pollution*, 100(1-3), 43-55.

Frondel, M., and Peters, J. (2007). "Biodiesel: A new Oilorado?" *Energy Policy*, 35(3), 1675-1684.

Gopalakrishnan, G., Negri, M. C., Wang, M., Wu, M., Snyder, S. W., and Lafreniere, L. (2009). "Biofuels, land, and water: A systems approach to sustainability." *Environmental Science & Technology*, 43(15), 6094-6100.

Granda, C., and Holtzapple, M. (2007). "MixAlco process: Biomass to carboxylic acids and alcohols." Personal Communication, College Station.

Granda, C. B., Zhu, L., and Holtzapple, M. T. (2007). "Sustainable liquid biofuels and their environmental impact." *Environmental Progress*, 26, 233-250.

Greene, N., and Roth, R. (2006). "Ethanol: Energy well spent: A review of corn and cellulosic ethanol energy balances in the scientific literature to date." *Industrial Biotechnology*, 2(1), 36-39.

Griffin, J. W. (2003). *Global climate change: The science, economics, and politics*, Edward Elgar Publishing Limited, Northhampton.

Guinee, J. "Headings for classification in life cycle assessment." *Workshop on Environmental Life Cycle Assessment of Products*, December 1-3, 1991. Leiden Brussels, 81-85.

Guinee, J. (2001). "Handbook on life cycle assessment: Operational guide to the ISO standards." *International Journal of Life Cycle Assessment*, 6(5), 255-255.

Hansen, J., Sato, M., Ruedy, R., Kharecha, P., Lacis, A., Miller, R., Nazarenko, L., Lo, K., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, S., Baum, E., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Cohen, A., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Jonas, J., Kelley, M., Kiang, N. Y., Koch, D., Labow, G., Lerner, J., Menon, S., Novakov, T., Oinas, V., Perlwitz, J., Rind, D., Romanou, A., Schmunk, R., Shindell, D., Stone, P., Sun, S., Streets, D., Tausnev, N., Thresher, D., Unger, N., Yao, M., and Zhang, S. (2007). "Dangerous human-made interference with climate: A GISS model study." *Atmospheric Chemistry and Physics*, 7(9), 2287-2312.

Heijungs, R., and Guinee, J. (1996). "Resource depletion in life-cycle assessment: Reply." *Environmental Toxicology and Chemistry*, 15(9), 1443-1444.

Heijungs, R., Guinée, J., Huppes, G., Lankreijer, H., Udo de Haes, H., Wegener Sleeswijk, A., Eggles, P., Duin, R., and de Goede, H. (1992). *Environmental life cycle assessment of products: Guide*, Leiden University, Leiden.

Hertel, T. W., Tyner, W. E., and Birur, D. K. "The global impacts of biofuel mandates." *Energy Journal*, 31(1), 75-100.

Hill, J., Nelson, E., Tilman, D., Polasky, S., and Tiffany, D. (2006). "Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels." *Proceedings of the National Academy of Sciences of the United States of America*, 103(30), 11206-11210.

Holtzapple, M. T., and Granda, C. B. (2009). "Carboxylate platform: The MixAlco process part 1: Comparison of three biomass conversion platforms." *Applied Biochemistry and Biotechnology*, 156(1-3), 525-536.

Hons, F. M., Moresco, R. F., Wiedenfeld, R. P., and Cothren, J. T. (1986). "Applied nitrogen and phosphorus effects on yield and nutrient-uptake by high-energy sorghum produced for grain and biomass." *Agronomy Journal*, 78(6), 1069-1078.

Huijbregts, M. A. J., Thissen, U., Guinee, J. B., Jager, T., Kalf, D., van de Meent, D., Ragas, A. M. J., Sleeswijk, A. W., and Reijnders, L. (2000a). "Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA." *Chemosphere*, 41(4), 541-573.

Huijbregts, M. A. J., Thissen, U., Jager, T., van de Meent, D., and Ragas, A. M. J. (2000b). "Priority assessment of toxic substances in life cycle assessment. Part II: assessing parameter uncertainty and human variability in the calculation of toxicity potentials." *Chemosphere*, 41(4), 575-588.

Institute for the Analysis of Global Security. (2004). "Threats to oil transport." Institute for the Analysis of Global Security. http://www.iags.org/oiltransport.html. May 7, 2011.

Intergovernmental Panel on Climate Change. (1992). *Climate change 1992: The supplementary report to the IPCC scientific assessment*, Cambridge University Press, New York.

Intergovernmental Panel on Climate Change. (1997). *Climate change 1995: The science of climate change: Contribution of working group I to the second assessment report of the Intergovernmental Panel on Climate Change* Cambridge University Press, New York.

Intergovernmental Panel on Climate Change. (2007a). *Climate change 2007: Impacts, adaptation, and vulnerability*, Cambridge University Press, New York.

Intergovernmental Panel on Climate Change. (2007b). *Climate change 2007: Mitigation of climate change*, Cambridge University Press, New York.

Intergovernmental Panel on Climate Change. (2007c). *Climate change 2007: The physical science basis*, Cambridge University Press, New York.

International Energy Agency. (2009). "World energy outlook 2010." Organization for Economic Co-Operatioin and Development, http://www.worldenergyoutlook.org /docs/weo2009. January 12, 2011.

International Standards Organization. (2006a). "Environmental management: Life cycle assessment: Principles and framework." *ISO 14040:2006(E)*, International Standards Organization, Geneva, Switzerland.

International Standards Organization. (2006b). "Environmental management: Life cycle assessment: Requirements and guidelines." *ISO 14044 2006(E)*, International Standards Organization, Geneva, Switzerland.

Intersociety Working Group. (2010). *AAAS Report XXXV: Research and Development FY2011*, American Association for the Advancement of Science, Washington D.C.

Jenkin, M. E., and Hayman, G. D. (1999). "Photochemical ozone creation potentials for oxygenated volatile organic compounds: Sensitivity to variations in kinetic and mechanistic parameters." *Atmospheric Environment*, 33(8), 1275-1293.

Jolliet, O., Muller-Wenk, R., Bare, J., Brent, A., Goedkoop, M., Heijungs, R., Itsubo, N., Pena, C., Pennington, D., Potting, J., Rebitzer, G., Stewart, M., de Haes, H. U., and Weidema, B. (2004). "The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative." *International Journal of Life Cycle Assessment*, 9(6), 394-404.

Kaltschmitt, M., Reinhardt, G. A., and Stelzer, T. (1997). "Life cycle analysis of biofuels under different environmental aspects." *Biomass & Bioenergy*, 12(2), 121-134.

Kellogg, R., Nehring, R., Grube, A., Goss, D., and Plotkin, S. (2000). "Environmental indicators of pesticide leaching and runoff from farm fields." National Resource Conservation Service. http://www.nrcs.usda.gov/technical/NRI/pubs/eip_pap.html. March 30, 2011.

Keve, Z., Verdi, J., and English, C. (2010). "State Policy Options." National Conference of State Legislatures. http://www.ncsl.org/documents/energy/biofuels-0110.pdf. March 30, 2011.

Kingdon, J. (2003). *Agendas, Alternatives, and Public Policies*, Addison-Wesley Educational Publishers, Inc., New York.

Kongshaug, G. (1998). "Energy consumption and greenhouse gas emission in fertilizer production." International Fertilizer Industry Association Technical Conference, International Fertilzer Industry Association, Marrakech, Morroco, 18.

Lau, M. H., Richardson, J. W., Outlaw, J. L., Holtzapple, M. T., and Ochoa, R. F. (2006). "The economics of ethanol from sweet sorghum using the MixAlco process." Agricultural and Food Policy Center, College Station, TX.

Low, S., and Isserman, A. (2008). "Ethanol: Implications for rural communities." American Agricultural Economics Association. http://ageconsearch.umn.edu/bitstream/6157/2/434083.pdf. March 30, 2011.

MacLean, H. L., Lave, L. B., Lankey, R., and Joshi, S. (2000). "A life-cycle comparison of alternative automobile fuels." *Journal of the Air & Waste Management Association*, 50(10), 1769-1779.

Miller, F. R., and Creelman, R. A. (1980). "Sorghum: a new fuel." 35th Annual American Seed Trade Association Annual Corn Sorghum Research Conference, H. D.

Loden and D. Wilkinson, eds., American Seed Trade Association, Chicago, Illinois, 219-232.

Miller, S. A. (2009). "Minimizing land use and nitrogen intensity of bioenergy." *Environmental Science and Technology*, 44(10), 3932-3939.

Minnesota Department of Agriculture. (2009). "Energy balance/life cycle inventory for ethanol, biodiesel and petroleum fuels." http://www.mda.state.mn.us /renewable/renewablefuels/balance.aspx. January 20, 2011.

Mohamadabadi, H. S., Tichkowsky, G., and Kumar, A. (2009). "Development of a multi-criteria assessment model for ranking of renewable and non-renewable transportation fuel vehicles." *Energy*, 34(1), 112-125.

Monti, A., Fazio, S., and Venturi, G. (2009). "Cradle-to-farm gate life cycle assessment in perennial energy crops." *European Journal of Agronomy*, 31(2), 77-84.

Muller, A. (2009). "Sustainable agriculture and the production of biomass for energy use." *Climatic Change*, 94(3-4), 319-331.

National Association of State Energy Officials. (2011). "State energy program." http://www.naseo.org/programs/sep/. January 25, 2011.

National Highway Traffic Safety Administration. (2010). "CAFE: fuel economy." http://www.nhtsa.gov/fuel-economy. January 25, 2011.

National Oceanic and Atmospheric Administration. (2010). "The instrumental record of past global temperatures." National Climate Data Center. http://www.ncdc. noaa.gov/paleo/globalwarming/instrumental.html. January 25, 2011.

National Research Council. (2007). *Water implications of biofuels production in the United States*, National Academies Press, Washington D.C.

Nebraska State Government. (2009). "Ethanol facilities capacity by state and plant." http://www.neo.ne.gov/statshtml/122.htm. December 21, 2010.

Obama, B., and Biden, J. (2008). "New energy for America." http://www. barackobama.com/pdf/factsheet_energy_speech_080308.pdf. December 13, 2010.

Oreskes, N. (2004). "Beyond the Ivory Tower, The Scientific Consensus on Climate Change." *Science*, 306, 1686.

Patzek, T. W., Anti, S. M., Campos, R., Ha, K. W., Lee, J., Li, B., Padnick, J., and Yee, S. A. (2005). "Ethanol from corn: Clean renewable fuel for the future, or drain on our resources and pockets?" *Environment, Development, and Sustainability*, 7, 319-336.

Perlack, R. D., Wright, L. L., Turhollow, A. F., Graham, R. L., Stokes, B. J., and Erbach, D. C. (2005). "Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply." *DOE/GO-102005-2135*, US Department of Energy, Oakridge.

Pesticide Action Network North America. (2010). "Pesticide Action Network pesticide database ", http://www.pesticideinfo.org/. January 26, 2011.

Petronella, G., Tung, A., Yusoff, M., Majid, N., Joo, G., and Huang, G. (2009). "Effect of N and K fertilizers on nutrient leaching and groundwater quality under mature oil palm in sabah during the monsoon period." *American Journal of Applied Sciences*, 6(10), 1788-1799.

Pimentel, D., Patzek, T., and Cecil, G. (2007). "Ethanol production: Energy, economic, and environmental losses." *Reviews of Environmental Contamination and Toxicology*, 189, 25-41.

Pimentel, D., Marklein, A., Toth, M. A., Karpoff, M. N., Paul, G. S., McCormack, R., Kyriazis, J., and Krueger, T. (2009). "Food versus biofuels: environmental and economic costs." *Human Ecology*, 37(1), 1-12.

Pimentel, D., Rodrigues, G., Wang, T., Abrams, R., Goldberg, K., Staecker, H., Ma, E., Brueckner, L., Trovato, L., Chow, C., Govindarajulu, U., and Boerke, S. (1994). "Renewable energy: Economic and environmental issues." *Bioscience*, 44(8), 536-547.

Port O. (2005). "Not your father's ethanol." Business Week, www.businessweek.com /magazine/content/d5-08/b3921117.htm. January 27, 2011.

Prabu, M. J. (2006). "Water hyacinth: Potential source for vermicompost." The Hindu. http://www.hindu.com/seta/2006/02/09/stories/2006020900241700.htm. May 7, 2011.

President's Council of Advisors on Science and Technology. (2010). "Accelerating the pace of change in energy technologies through an integrated federal energy policy." http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-energy-tech-report.pdf. March 30, 2011.

Puppan, D. (2002). "Environmental evaluation of biofuels." *Periodica Polytechnica Ser. Soc. Man. Sci.*, 10(1), 95-116.

Renewable Energy World. (2010). "Big oil still likes cellulosic ethanol." http://www.renewableenergyworld.com/rea/news/print/article/2010/08/big-oil-still-likes-cellulosic-ethanol. January 27, 2011.

Romm, J. (2006). "The car and fuel of the future." *Energy Policy*, 34(17), 2609-2614.

Samaras, C., and Meisterling, K. (2008). "Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy." *Environmental Science & Technology*, 42(9), 3170-3176.

Sandia National Laboratories. (2006). "Energy demands on water resources: Report to congress on the interdependency of energy and water." US Department of Energy. http://www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf. March 30, 2011.

Sathre, R., Gustavsson, L., and Bergh, J. (2010). "Primary energy and greenhouse gas implications of increasing biomass production through forest fertilization." *Biomass & Bioenergy*, 34(4), 572-581.

Schmer, M. R., Vogel, K. P., Mitchell, R. B., and Perrin, R. K. (2008). "Net energy of cellulosic ethanol from switchgrass." *Proceedings of the National Academy of Sciences of the United States of America*, 105(2), 464-469.

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F. X., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., and Yu, T. H. (2008). "Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change." *Science*, 319(5867), 1238-1240.

Shapouri, H., Duffield, J. A., and Wang, M. (2003). "The energy balance of corn ethanol revisited." *Transactions of the Asae*, 46(4), 959-968.

Shapouri, H., and McAloon, A. (2001). "The 2001 net energy balance of corn ethanol." US Department of Agriculture. http://www.usda.gov/oce/reports/energy /net_energy_balance.pdf. March 30, 2011.

Sharpley A. N., Daniel T., Sims T., Lemunyon J., Stevens R., and R., P. (2003). "Agricultural phosphorus and eutrophication." *ARS-149*, US Department of Agriculture, Pasture Systems and Research Department, University Park, PA.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., and Shapouri, H. (1998). "Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus." *NREL/SR-580-24089*, U.S. Department of Energy.

Sierra, R., Smith, A., Granda, C., and Holtzapple, M. T. (2008). "Producing fuels and chemicals from lignocellulosic biomass." *Chemical Engineering Progress*, 104(8), S10-S18.

Sleeswijk, A. W., van Oers, L., Guinee, J. B., Struijs, J., and Huijbregts, M. A. J. (2007). "Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000." *Science of the Total Environment*, 390(1), 227-240.

Smeets, E. M. W., Bouwmanw, L. F., Stehfest, E., van Vuuren, D. P., and Posthuma, A. (2009). "Contribution of N2O to the greenhouse gas balance of first-generation biofuels." *Global Change Biology*, 15(1), 1-23.

Sneller, T., and Durante, D. (2008). "The impact of ethanol production on food, feed, and fuel." Issue Brief, Ethanol Across America. http://www.ne-ethanol.org /pdf/FoodandFuel2008.pdf. March 29, 2011.

St Clair, S., Hillier, J., and Smith, P. (2008). "Estimating the pre-harvest greenhouse gas costs of energy crop production." *Biomass & Bioenergy*, 32(5), 442-452.

Swenson, D. (2008). "Ethanol's economic impact on rural communities." AgMRC Renewable Energy Newsletter, Agricultural Marketing Resource Center. http://www.agmrc.org/renewable_energy/renewable_energy/ethanols_economic _impact_on_rural_communities.cfm. January 25, 2011.

Terrabon. (2010). "Demonstration plant." Terrabon LLC. http://www.terrabon.com /mixalco_semiworksplant.php. January 29, 2011., College Station, TX.

Thomas, G. (2000). "Overview of storage development: DOE hydrogen program." US Department of Energy. http://www1.eere.energy.gov/hydrogenandfuelcells /pdfs/storage.pdf. November 11, 2010.

Tilman, D., Hill, J., and Lehman, C. (2006). "Carbon-negative biofuels from low-input high-diversity grassland biomass." *Science*, 314(5805), 1598-1600.

Tyner, W. E., Taheripour, F., and Perkis, D. (2010). "Comparison of fixed versus variable biofuels incentives." *Energy Policy*, 38(10), 5530-5540.

Ugarte, D. G. D., He, L. X., Jensen, K. L., and English, B. C. (2010). "Expanded ethanol production: Implications for agriculture, water demand, and water quality." *Biomass & Bioenergy*, 34(11), 1586-1596.

US Agency for International Development. (2001). "The water-energy nexus: Opportunities for integrated environmental management." USAID Global Environment Center Environment Notes, Environment Information Clearinghouse. http://www.usaid.gov/our_work/environment/water/enviro.notes /enviro.notes.water-energy.pdf. November 12, 2010.

US Department of Energy. (2009). "Obama Administration Announces More Than $327 Million in Recovery Act Funding for Science Research."

Vaughan V. (2011). "Valero invests in commercial-scale biorefinery." mysanantonio.com, http://www.mysanantonio.com/business/article/Valero-invests-in-commercial-scale-biorefinery-955430.php. March 25, 2011.

Virkajarvi, P., Maljanen, M., Saarijarvi, K., Haapala, J., and Martikainen, P. J. (2010). "N2O emissions from boreal grass and grass-clover pasture soils." *Agriculture Ecosystems & Environment*, 137(1-2), 59-67.

Visalli, D. (2006). "Getting a decent return on your energy investment." Energy Bulletin, Post Carbon Institute. http://www.energybulletin.net/node/14745. March 25, 2011.

von Blottnitz, H., and Curran, M. A. (2007). "A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective." *Journal of Cleaner Production*, 15(7), 607-619.

Wang, D., Bean, S., McLaren, J., Seib, P., Madl, R., Tuinstra, M., Shi, Y., Lenz, M., Wu, X., and Zhao, R. (2008). "Grain sorghum is a viable feedstock for ethanol production." *Journal of Industrial Microbiology & Biotechnology*, 35(5), 313-320.

Weitz, K., Sharma, A., Vigon, B., Price, E., Norris, G., Eagan, P., Owens, W., and Veroutis, A. (1998). "Streamlined life cycle assessment: a final report from the SETAC North America streamlined LCA workgroup." J. A. Todd and M. A. Curran, eds., Society of Environmental Toxicology and Chemistry. http://www.ertc.deqp.go.th/ertc/images/stories/user/ct/ct1/cp/design_for_environment/Streamlined%20LCA.pdf. March 30, 2011.

Whitehouse. (2010). "Catalyze breakthroughs for national priorities." Issues, http://www.whitehouse.gov/issues/economy/innovation/breakthroughs. December 13, 2010., Article about the national priorities.

World Business Council for Economic Development. (2006). "WBCSD outlines key elements for future climate framework." Press Release, http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MjE1MTU. March 25, 2011.

World Meteorological Organization. (1992). *Scientific assessment of stratospheric ozone depletion: 1991*, Global Ozone Research and Monitoring Project Number 25, Geneva, Switzerland.

World Meteorological Organization. (1995). *Scientific assessment of ozone depletion: 1994*, Global Ozone Research and Monitoring Project Number 37, Geneva, Switzerland.

Wyman, C. E. (2007). "What is (and is not) vital to advancing cellulosic ethanol." *Trends in Biotechnology*, 25(4), 153-157.

Zhao, X., Xie, Y. X., Xiong, Z. Q., Yan, X. Y., Xing, G. X., and Zhu, Z. L. (2009). "Nitrogen fate and environmental consequence in paddy soil under rice-wheat rotation in the Taihu lake region, China." *Plant and Soil*, 319(1-2), 225-234.

Zhu, L., O'Dwyer, J. P., Chang, V. S., Granda, C. B., and Holtzapple, M. T. (2008). "Structural features affecting biomass enzymatic digestibility." *Bioresource Technology*, 99(9), 3817-3828.

Zhuang, S. Y., and Wang, M. K. (2009). "Model estimation of ammonia volatilization from a paddy rice field after application of a surface film-forming material." *Journal of Agricultural Science*, 148, 95-100.

APPENDIX A

Table 20. Inventory Analysis Inputs for Resource Provisioning Life Stage

Resource Provisioning							
Material Inputs			Data Pedigree Matrix				
Fertilizers							
Fertilizer	kg/yr	Reference	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Further Technical Correlation
Nitrogen	1.79E+06	Rooney (2010)	1	1	1	1	1
Potassium	0.00E+00	Rooney (2010)	1	1	1	1	1
Phosphorus	1.22E+06	Rooney (2010)	1	1	1	1	1
Zinc	9.57E+04	Rooney (2010)	1	1	1	1	1
Pesticides/ Herbicides							
Pesticide/ Herbicide	kg/yr						
Atrazine	2.68E+04	Rooney (2010), Pesticide Action Network (2010)	4	1	1	4	1
Water							
Water	kg/yr						
Water	0.00E+00	Rooney (2010)	1	1	1	1	1
Land							
Land	acres/yr	Reference					
Land	5.27E+04	Granda et al. (2007), Lau et al. (2006), Rooney (2010)	2	1	1	1	1
Energy							
Energy	MJ/yr	Reference					
Fossil	1.36E+07	Granda et al. (2007)	2	2	2	1	1
Other							
	number/acre-yr						
seeds	1.63E+09	Rooney (2010)	1	1	1	1	1

Table 21. Inventory Analysis Outputs for Resource Provisioning Life Stage

Resource Provisioning							
Material Output			Data Pedigree Matrix				
Emissions							
	kg/yr	Reference	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Further Technical Correlation
Nitrous Oxide (N2O)	2.24E+04	Bouwman (1996), Crutzen et al. (2008), Zhau et al. (2009)	2	2	2	3	2
Ammonia (NH3)	3.14E+04	Barbanti et al. (2006), Zhau et al. (2009)	2	2	2	3	2
Nitric Oxide (NO)	1.26E+04	Zhau et al. (2009)	2	2	2	3	2
Leaching into Fresh Water							
Emission	kg/yr	Reference					
Nitrogen	2.33E+04	Petronella et al. (2009)	2	2	2	3	2
Phosphorus	1.83E+04	Dalgaard et al. (2006)	2	2	2	3	2
Potassium	0.00E+00	Petronella et al. (2009)	2	2	2	3	2
Atrazine	1.34E+02	Kellogg et al. (2000)	2	2	2	3	2
Percolating into Soil							
Emission	kg/yr	Reference					
Atrazine	1.34E+02	Kellogg et al. (2000)	2	2	2	3	2

Table 22. Inventory Analysis Inputs for Pretreatment/Fermentation Life Stage

Pretreatment/Fermentation							
Material Input			Data Pedigree Matrix				
Water							
	m3/yr	Reference	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Further Technical Correlation
water	9.73E+06	Granda and Holtzapple (2007)	1	1	1	1	1
Land							
Land	acres/yr	Reference					
Land	0.00E+00	Granda and Holtzapple (2007)	2	1	1	1	1
Energy							
Engergy	MJ/yr	Reference					
Fossil	0.00E+00	Granda and Holtzapple (2007)	2	1	1	1	1
Other							
	kg/yr	Reference					
Micro-organisms		Granda and Holtzapple (2007)	2	1	1	1	1
Calcium Carbonate	4.80E+07	Granda and Holtzapple (2007)	1	1	1	1	1
Manure	6.40E+07	Granda and Holtzapple (2007)	1	1	1	1	1

Table 23. Inventory Analysis Outputs for Pretreatment/Fermentation Life Stage

Pretreatment/Fermentation							
Material Output			Data Pedigree Matrix				
Emissions							
Emission	kg/yr	Reference	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Further Technical Correlation
Carbon Dioxide	2.49E+02	Granda and Holtzapple (2007)	1	1	1	1	1
Hydrogen sulfide	negligible mass	Granda and Holtzapple (2007)	1	1	1	1	1
Mercaptans	negligible mass	Granda and Holtzapple (2007)	1	1	1	1	1
Amines	negligible mass	Granda and Holtzapple (2007)	1	1	1	1	1
Pinenes	negligible mass	Granda and Holtzapple (2007)	1	1	1	1	1

Table 24. Inventory Analysis Inputs for Primary Operation Life Stage

Primary Operation							
Material Input			**Data Pedigree Matrix**				
Water							
Water	**m3/yr**	**Reference**	**Reliability**	**Completeness**	**Temporal Correlation**	**Geographical Correlation**	**Further Technical Correlation**
Water	1.69E+07	Granda and Holtzapple (2007)	**1**	**1**	**1**	**1**	**1**
Land							
Land	**acres/yr**						
Land	0.00E+00	Granda and Holtzapple (2007)	2	1	1	1	1
Energy							
Energy	MJ/yr						
Fossil	0.00E+00	Granda and Holtzapple (2007)	2	1	1	1	1
Other							
		Reference					
Hydrogen (kg/yr)	1.10E+07	Granda and Holtzapple (2007)	1	1	1	1	1
Polyacrylamide kg floc/yr	4.45E+05	Granda and Holtzapple (2007)	1	1	1	1	1
Raney Nickel Catalyst kl/yr for	3.25E+05	Granda and Holtzapple (2007)	1	1	1	1	1

Table 25. Inventory Analysis Outputs for Primary Operation

Primary Operation							
Material Output			**Data Pedigree Matrix**				
		Reference	**Reliability**	**Completeness**	**Temporal Correlation**	**Geographical Correlation**	**Further Technical Correlation**
Product-fuel (ML/yr)	1.71E+02	Granda and Holtzapple (2007)	1	1	1	1	1
Liquid waste (L/yr)	1.22E+04	Granda and Holtzapple (2007)	1	1	1	1	1

Table 26. Sensitivity Analysis for Nitrous Oxide Emissions

	Emission Rate of Nitrous Oxide	Emmitted Nitrous Oxide	Climate Change Potential
	0.001	1.79E+03	4.19E+06
	0.0025	4.49E+03	5.02E+06
	0.0035	6.28E+03	5.58E+06
	0.0045	8.07E+03	6.13E+06
	0.0055	9.87E+03	6.69E+06
	0.0065	1.17E+04	7.25E+06
	0.0075	1.35E+04	7.80E+06
	0.0085	1.53E+04	8.36E+06
	0.0095	1.70E+04	8.91E+06
	0.0105	1.88E+04	9.47E+06
	0.0115	2.06E+04	1.00E+07
	0.0125	2.24E+04	1.06E+07
	0.0135	2.42E+04	1.11E+07
	0.0145	2.60E+04	1.17E+07
	0.0155	2.78E+04	1.23E+07
	0.0165	2.96E+04	1.28E+07
	0.0175	3.14E+04	1.34E+07
	0.0185	3.32E+04	1.39E+07
	0.0195	3.50E+04	1.45E+07
	0.0205	3.68E+04	1.50E+07
	0.0215	3.86E+04	1.56E+07
	0.0225	4.04E+04	1.61E+07
	0.0235	4.22E+04	1.67E+07
	0.0245	4.40E+04	1.73E+07
	0.0255	4.58E+04	1.78E+07
	0.0265	4.75E+04	1.84E+07
	0.0275	4.93E+04	1.89E+07
	0.0285	5.11E+04	1.95E+07
	0.0295	5.29E+04	2.00E+07
	0.0305	5.47E+04	2.06E+07
	0.0315	5.65E+04	2.12E+07
	0.0325	5.83E+04	2.17E+07
	0.0335	6.01E+04	2.23E+07
	0.0345	6.19E+04	2.28E+07
	0.0355	6.37E+04	2.34E+07
	0.0365	6.55E+04	2.39E+07
	0.0375	6.73E+04	2.45E+07
	0.0385	6.91E+04	2.50E+07
	0.0395	7.09E+04	2.56E+07
	0.0405	7.27E+04	2.62E+07
	0.0415	7.45E+04	2.67E+07
	0.0425	7.63E+04	2.73E+07
	0.0435	7.80E+04	2.78E+07
	0.0445	7.98E+04	2.84E+07
	0.0455	8.16E+04	2.89E+07
	0.0465	8.34E+04	2.95E+07
	0.0475	8.52E+04	3.01E+07
	0.0485	8.70E+04	3.06E+07
	0.0495	8.88E+04	3.12E+07
	0.0505	9.06E+04	3.17E+07
Percentage Change	1.0%		0.89%
Percentage Increase (from assumed case to worst case)			67%

Table 27. Sensitivity Analysis for Ammonia Emissions

Sensitivity Analysis for NH_3 Emissions					
	Emission Rate of Ammonia	Emmitted Ammonia	Acidification Potential	Eutrophication Potential	Human Toxicity Potential
	0.0100	17942.1	34987.1	73709.7	20295.1
	0.0103	18480.3	35848.3	73898.0	20349.0
	0.0106	19018.6	36709.5	74086.4	20402.8
	0.0109	19556.9	37570.7	74274.8	20456.6
	0.0112	20095.1	38431.9	74463.2	20510.4
	0.0115	20633.4	39293.2	74651.6	20564.3
	0.0118	21171.7	40154.4	74840.0	20618.1
	0.0121	21709.9	41015.6	75028.4	20671.9
	0.0124	22248.2	41876.8	75216.8	20725.7
	0.0127	22786.4	42738.0	75405.2	20779.6
	0.0130	23324.7	43599.3	75593.6	20833.4
	0.0133	23863.0	44460.5	75782.0	20887.2
	0.0136	24401.2	45321.7	75970.4	20941.0
	0.0139	24939.5	46182.9	76158.7	20994.9
	0.0142	25477.8	47044.1	76347.1	21048.7
	0.0145	26016.0	47905.4	76535.5	21102.5
	0.0148	26554.3	48766.6	76723.9	21156.3
	0.0151	27092.5	49627.8	76912.3	21210.2
	0.0154	27630.8	50489.0	77100.7	21264.0
	0.0157	28169.1	51350.2	77289.1	21317.8
	0.0160	28707.3	52211.5	77477.5	21371.6
	0.0163	29245.6	53072.7	77665.9	21425.5
	0.0166	29783.9	53933.9	77854.3	21479.3
	0.0169	30322.1	54795.1	78042.7	21533.1
	0.0172	30860.4	55656.3	78231.1	21587.0
	0.0175	31398.6	56517.6	78419.4	21640.8
	0.0178	31936.9	57378.8	78607.8	21694.6
	0.0181	32475.2	58240.0	78796.2	21748.4
	0.0184	33013.4	59101.2	78984.6	21802.3
	0.0187	33551.7	59962.4	79173.0	21856.1
	0.0190	34090.0	60823.7	79361.4	21909.9
	0.0193	34628.2	61684.9	79549.8	21963.7
	0.0196	35166.5	62546.1	79738.2	22017.6
	0.0199	35704.7	63407.3	79926.6	22071.4
	0.0202	36243.0	64268.5	80115.0	22125.2
	0.0205	36781.3	65129.8	80303.4	22179.0
	0.0208	37319.5	65991.0	80491.8	22232.9
	0.0211	37857.8	66852.2	80680.2	22286.7
	0.0214	38396.1	67713.4	80868.5	22340.5
	0.0217	38934.3	68574.6	81056.9	22394.3
	0.0220	39472.6	69435.8	81245.3	22448.2
	0.0223	40010.8	70297.1	81433.7	22502.0
	0.0226	40549.1	71158.3	81622.1	22555.8
	0.0229	41087.4	72019.5	81810.5	22609.7
	0.0232	41625.6	72880.7	81998.9	22663.5
	0.0235	42163.9	73741.9	82187.3	22717.3
	0.0238	42702.2	74603.2	82375.7	22771.1
	0.0241	43240.4	75464.4	82564.1	22825.0
	0.0244	43778.7	76325.6	82752.5	22878.8
	0.0247	44316.9	77186.8	82940.9	22932.6
	0.0250	44855.2	78048.0	83129.2	22986.4
Percent Change	1.000%		**0.9%**	**0.2%**	**0.2%**
Percentage Increase (from assumed case to worst case)			**38.1%**	**6.0%**	**6.2%**

Table 28. Sensitivity Analysis of Nitrogen Emissions

Sensitivity Analysis for N Emissions			
	Emission Rate of Nitrogen	**Emmitted Nitrogen**	**Eutrophication Potential**
	0.0100	17942.080	76158.747
	0.0102	18211.211	76271.782
	0.0103	18480.342	76384.817
	0.0105	18749.474	76497.852
	0.0106	19018.605	76610.887
	0.0108	19287.736	76723.922
	0.0109	19556.867	76836.958
	0.0111	19825.998	76949.993
	0.0112	20095.130	77063.028
	0.0114	20364.261	77176.063
	0.0115	20633.392	77289.098
	0.0117	20902.523	77402.133
	0.0118	21171.654	77515.168
	0.0120	21440.786	77628.203
	0.0121	21709.917	77741.238
	0.0123	21979.048	77854.274
	0.0124	22248.179	77967.309
	0.0126	22517.310	78080.344
	0.0127	22786.442	78193.379
	0.0129	23055.573	78306.414
	0.0130	23324.704	78419.449
	0.0132	23593.835	78532.484
	0.0133	23862.966	78645.519
	0.0135	24132.098	78758.554
	0.0136	24401.229	78871.589
	0.0138	24670.360	78984.625
	0.0139	24939.491	79097.660
	0.0141	25208.622	79210.695
	0.0142	25477.754	79323.730
	0.0144	25746.885	79436.765
	0.0145	26016.016	79549.800
	0.0147	26285.147	79662.835
	0.0148	26554.278	79775.870
	0.0150	26823.410	79888.905
	0.0151	27092.541	80001.941
	0.0153	27361.672	80114.976
	0.0154	27630.803	80228.011
	0.0156	27899.934	80341.046
	0.0157	28169.066	80454.081
	0.0159	28438.197	80567.116
	0.0160	28707.328	80680.151
Percent Change	1.00%		**0.148%**
Percent Increase (from assumed case to worst case)			**2.9%**

Table 29. Sensitivity Analysis of Phosphorus Emissions

	Emission Rate of Phosphorus	Emmitted Phosphorus	Eutrophication Potential
	0.0100	12200.614	59752.509
	0.0103	12505.630	60685.856
	0.0105	12810.645	61619.203
	0.0108	13115.660	62552.550
	0.0110	13420.676	63485.897
	0.0113	13725.691	64419.244
	0.0115	14030.707	65352.591
	0.0118	14335.722	66285.938
	0.0120	14640.737	67219.285
	0.0123	14945.753	68152.632
	0.0125	15250.768	69085.979
	0.0128	15555.783	70019.326
	0.0130	15860.799	70952.673
	0.0133	16165.814	71886.020
	0.0135	16470.829	72819.367
	0.0138	16775.845	73752.714
	0.0140	17080.860	74686.061
	0.0143	17385.876	75619.408
	0.0145	17690.891	76552.755
	0.0148	17995.906	77486.102
	0.0150	18300.922	78419.449
	0.0153	18605.937	79352.796
	0.0155	18910.952	80286.143
	0.0158	19215.968	81219.490
	0.0160	19520.983	82152.837
	0.0163	19825.998	83086.184
	0.0165	20131.014	84019.531
	0.0168	20436.029	84952.878
	0.0170	20741.044	85886.225
	0.0173	21046.060	86819.572
	0.0175	21351.075	87752.919
	0.0178	21656.091	88686.266
	0.0180	21961.106	89619.613
	0.0183	22266.121	90552.960
	0.0185	22571.137	91486.307
	0.0188	22876.152	92419.654
	0.0190	23181.167	93353.001
	0.0193	23486.183	94286.348
	0.0195	23791.198	95219.695
	0.0198	24096.213	96153.042
	0.0200	24401.229	97086.389
Percent Change	1.0%		**0.764%**
Percent Increase (from assumed case to worst case)			**23.8%**

Table 30. Sensitivity Analysis of Atrazine Emissions

	Application Rate	Applied Atrazine	Emitted Atrazine	Freshwater Aquatic Ecological	Terrestrial Ecological Toxicity Potential	Human Toxicity Potential
	0.77	1.84E+04	9.21E+01	460513.3867	607.8776704	20569.0397
	0.892	2.13E+04	106.6955691	533477.8453	704.1907558	20942.6178
	1.014	2.43E+04	121.2884608	606442.304	800.5038413	21316.1958
	1.12	2.68E+04	133.9675307	669837.6533	884.1857024	21640.78
	1.136	2.72E+04	135.8813525	679406.7627	896.8169267	21689.7738
	1.258	3.01E+04	150.4742443	752371.2213	993.1300122	22063.3519
	1.38	3.30E+04	165.067136	825335.68	1089.443098	22436.9299
	1.502	3.59E+04	179.6600277	898300.1387	1185.756183	22810.5079
	1.624	3.89E+04	194.2529195	971264.5973	1282.069268	23184.0859
	1.746	4.18E+04	208.8458112	1044229.056	1378.382354	23557.664
	1.868	4.47E+04	223.4387029	1117193.515	1474.695439	23931.242
	1.99	4.76E+04	238.0315947	1190157.973	1571.008525	24304.82
	2.112	5.05E+04	252.6244864	1263122.432	1667.32161	24678.3981
	2.234	5.34E+04	267.2173781	1336086.891	1763.634696	25051.9761
	2.356	5.64E+04	281.8102699	1409051.349	1859.947781	25425.5541
	2.478	5.93E+04	296.4031616	1482015.808	1956.260867	25799.1321
	2.6	6.22E+04	310.9960533	1554980.267	2052.573952	26172.7102
	2.722	6.51E+04	325.5889451	1627944.725	2148.887037	26546.2882
	2.844	6.80E+04	340.1818368	1700909.184	2245.200123	26919.8662
	2.966	7.10E+04	354.7747285	1773873.643	2341.513208	27293.4443
	3.088	7.39E+04	369.3676203	1846838.101	2437.826294	27667.0223
	3.21	7.68E+04	383.960512	1919802.56	2534.139379	28040.6003
Percent Change		1.00%		1.00%	1.00%	0.34%
Percent Increase (from assumed case to worst case)				186.61%	186.61%	29.573%

VITA

Lisa Diane Hurtado currently holds the position of Assistant Vice President for Federal Agency Advancement at Texas A&M University. In her role, Dr. Hurtado is responsible for strengthening ties and developing relationships between the campus community and federal research sponsors, particularly with the mission-driven agencies. Dr. Hurtado also monitors emerging funding priorities among federal agencies to best position the University for leadership in new research areas and informs the agencies regarding research and development strengths at Texas A&M that to demonstrate how the University can assist agency goals.

Dr. Hurtado has served in various roles at Texas A&M starting in 2001 including Director of Engineering Student Services and Academic Programs, Research Initiatives Officer, and as a research engineer. Prior to her service at Texas A&M, she held engineering positions at Sandia National Laboratories, Lockheed, and Pratt & Whitney.

Dr. Hurtado received a bachelor and master of science degree in Aerospace Engineering, and a doctor of philosophy degree in Interdisciplinary Engineering, all from Texas A&M University.

Address:

Office of Government Relations

Texas A&M University

1246 TAMU

College Station, Texas 77843-1246